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AUTHORITY
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488983

SILVER-ZINC MISSILE POWER SUPPLY

Fourth Quarterly Technical Progress Report

July - 1966

Air Force Aero Propulsion Laboratory
Research and Technology Division
Air Force Systems Command, USAF.
Wright-Patterson AFB, Ohio 45433

Project No. 8173

Task No. 817304-28

Prepared Under Contract No. AF 33(615) 2663

by

YARDNEY ELECTRIC CORPORATION
New York, N.Y.

Author: R. F. Chireau

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SILVER-ZINC MISSILE POWER SUPPLY

Author: R. F. Chireau

FOREWORD

This is the fourth quarterly report prepared by Yardney Electric Corporation, New York, New York, on Air Force Contract AF 33 (615) 2663 under Task No. 817304-28: Batteries, of Project No. 8173, Static Energy Conversion. This work was sponsored by the Air Force Aero-Propulsion Laboratory of the Research and Technology Division and the Ballistic Systems Division of the U. S. Air Force. It was administered under technical guidance of the Air Force Aero-Propulsion Laboratory, Wright-Patterson Air Force Base, Ohio.

This report is being published and distributed prior to Air Force review. The publication of this report, therefore, does not constitute approval by the Air Force of the findings or conclusions contained herein. It is published for the exchange and stimulation of ideas.

ABSTRACT

1. "All battery" design approaches using duplex electrodes (pile construction) are described and design parameters compiled.

2. The experimental work performed to verify the various cell and battery designs has been outlined. Data and test results are analyzed.

3. Design guidelines for a 1500 VOH, 750 watt-hour battery module are summarized.

4. Extensive data on battery size and weight versus battery voltage have been compiled for batteries having outputs of 2 KW to 20 KW.

   Formulae expressing the weight and volume of batteries as a function of nominal battery terminal voltage, watt-hour rating and percent regulation are presented for batteries utilizing conventional (individual) cells.

5. The study phase of the DC-DC converter development program is in progress.

   A report which documents the effort expended by The Ordnance Division of Honeywell, Inc. during the preceding quarter is included in the Appendix of this report.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

I INTRODUCTION

This document represents the fourth quarterly report as defined in contract # AF-33(615)2663 - Exhibit "B", Item III, dated 8 June, 1965.

It is the purpose of this contract to conduct a program of study, design and development leading to the fabrication of a high rate silver-zinc missile power supply capable of meeting the requirements listed in the Statement of Work, Part I, Schedule, page A.

Three possible approaches are to be considered in the design of the power supply unit:

(a) The power supply package consists of a silver-zinc battery (or batteries) only.

(b) The power supply package consists of a silver-zinc battery (or batteries) in combination with a static power converter with the converter supplying all the loads.

(c) The power supply package consists of a silver-zinc battery (or batteries) in combination with a device carrying partial loads.

The program itself has been divided into two phases:

<u>Phase I</u> : Trade-off and Investigation.- This phase constitutes a through study to determine the optimum design approach to the Missile Power Supply.

<u>Phase II</u>: Development, fabrication and testing of Power Supply units designed in accordance with the results of investigations conducted in the study program.

This report presents the work performed during the period April 1 1966 - June 30 1966, and covers the progress on Phase I of the program.

II DISCUSSION

Trade-Off and Optimization Investigation.

1.0 The use of batteries to supply the load directly.

1.1 The "all battery" duplex electrode approach to the design of the power supply.

1.1.1 Our studies have shown that the conventional cell approach to the "all battery" version of the power supply, while feasible, would result in a power supply having an optimum overall weight of 30.5 lbs. and a volume of 1188 cubic inches.

Utilizing the duplex electrode construction in a "square cell" geometry, we obtained a total battery weight of 13.7 lbs. in a volume of 296 cubic inches. Further work established that a volume reduction of about thirty (30) cubic inches could be realized through the optimization of the square cell duplex electrode battery.

1.1.2 The "square cell" duplex electrode battery.

Having established a battery design layout which could meet the requirements of the contract Statement of Work, the program plan called for substantiation of the design by assembling, testing and evaluating battery modules which are essentially scaled-down models of the complete battery.

1.1.2.1 Experimental:

Previous progress reports have dealt with the evaluation of duplex electrode modules of 4 cells, 10 cells, 17 cells, and 40 cells. The main effort during the past quarter was devoted to (a) the construction and test of one hundred cell (180 volts) modules (b) the design and breadboard of a high voltage battery module in order to substantiate the design concept of the proposed square cell duplex electrode battery (c) an additional task was to establish techniques to manufacture large quantities of thin (0.0015 - 0.0025 in.) electrodes.

1.1.2.1.1 Battery Tests on 100 Cell Modules.

Battery PB019 consisted of 100 duplex electrode cells in series. Gasket thickness was 0.020" and the electrolyte inlet feed channel measured 1/16" w x 0.020" t x 1/4" l (cross sectional area 0.0125 sq. in.). The electrode pairs were cemented to the gasket plates using 3M structural adhesive #EC 2216B. The assemblies were then stacked and the entire compressed by means of tie rods. The battery measured 2-5/8" x 2-5/8" x 2-3/8" not including the activation mechanism.

The battery was activated using 100 cc of electrolyte (38% potassium hydroxide), under no load conditions. Note that all one hundred cells were activated as a group and therefore were connected hydraulically

in series through the electrolyte in the feed manifold.

Five seconds after activation a voltage of 155 volts was attained, (this is about 10 volts lower than the normal open circuit voltage expected from a hundred cell battery) no gassing was observed in the electrolyte manifold channel, however, the battery voltage began to drop (reaching 140 volts at t = 15 seconds, 127 volts at t = 30 seconds, 125 volts at t = 45 seconds, 113 volts at t = 60 seconds, 70 volts at t = 75 seconds) indicating a rather strong intercell leakage current in the battery.

The test was interrupted two minutes after battery activation. Battery 020 consisted also of one hundred cells in series. The battery construction was identical to that of PB019 except that the electrode gaskets were bonded with epoxy resin and the battery pack encapsulated in potting.

The battery was activated using 90 cc of electrolyte (38% potassium hydroxide), under no load conditions.

Activation was normal and the open circuit voltage rose to 163 volts in five seconds. After thirty seconds, the electrolyte in the feed manifold began to gas and the battery voltage dropped from 163 to 158 volts. The unit was discharged at this point (discharge current: 2.5 amps, corresponding to a current density of 0.8 amp. per sq. in.) and gave the following data:

Time (Seconds)	Voltage (Volts)
5"	113
15"	93
20"	90.1
30"	70.5
35"	46.5

It appears that (a) the individual duplex gaskets must be bonded to reduce intercell leakage paths around the cell edges (b) the size of the manifold must be reduced (c) leakage current must be controlled by dividing the series connected cells into relatively small groups (modules) and activating each module through a separate channel.

The previous tests have thus established that the leakage current in the one hundred cell modules tested was due largely to the nature of the manifold construction and the gasket seal used. A likely method of coping with this problem would be to use grooves or channels to distribute the electrolyte to individual module groups. The number of cells in a single group should be small enough to limit intercell leakage in the group and has to be determined empirically. The proper size manifold channel, in effect, limits the inter-group current flow. As a start, the number of cells per group was set at twenty.

The purpose of the next series of tests was essentially to verify the design of an improved battery manifold design and methods of sealing individual duplex gaskets.

Battery PB021:

This unit consisted of one hundred 0.06 ampere-hour cells in series. The following parameters apply:

(a) Gasket thickness: .020"
(b) Electrolyte feed channel: 1/16" w x 0.020" x 1/4"
(c) No. of cells per module subgroup: 20
(d) Electrode gaskets bonded with Eastman 910 adhesive
(e) Battery pack encapsulated in epoxy resin

The five 20 cell groups were stacked and connected in electrical series prior to positioning of the manifold feed block and subsequent encapsulating operation.

The battery was activated using 90 cc of electrolyte (38% potassium hydroxide), under no load conditions.

Activation was normal and the open circuit voltage rose to 171 volts, two seconds after activation. At t=60 seconds the unit was discharged at 3.5 amps (1.1 A/in^2) and gave the following data:

TIME (SECONDS)	100 CELL BATTERY VOLTAGE (VOLTS)	FIRST 20 CELL MODULE VOLTAGE (VOLTS)	FIFTH 20 CELL MODULE VOLTAGE (VOLTS
2.5"	57.5	28.0	13.5
5.0"	35.0	25.0	8.1

The test was interrupted at this point, because of the apparent imbalance between cell groups due to poor electrolyte distribution, and ten cubic centimeters of electrolyte were added to the battery. The unit was then discharged at 3.5 amps. The following data was obtained:

TIME (SECONDS)	100 CELL BATTERY VOLTAGE (VOLTS)	FIRST 20 CELL MODULE VOLTAGE (VOLTS)	FIFTH 20 CELL MODULE VOLTAGE (VOLTS)
OCV	170	32.8	32
2.5"	141	29.2	25.5
5.0"	138	29.0	23.0
10"	130	28.6	21.8
15"	123	28.3	21.0
20"	115	27.6	19.5
30"	104	25.2	16.8

The test was interrupted two minutes after battery activation. There was no sign of arcing in the electrolyte feed manifold and, after the test discharge, the battery voltage recovered to a normal open circuit voltage (approximately 1.55 volts per cell).

Battery PB022:

This unit was similar to battery PB021 except that it consisted of one hundred 0.06 ampere-hour cells activated in hydraulic parallel but not electrically interconnected. The battery pack was divided into twenty cell sections, each section being activated through separate manifold channels. A pair of leads extended from each twenty cell stack. After activation, the five groups were connected electrically in series by means of knife switches.

The battery was activated using 90 cc of electrolyte (38% potassium hydroxide), under no load conditions.

One minute after activation, the 100 cells were placed in series and the unit discharged at 3.5 amps (1.1 amps. per sq. in.). The following discharge data was obtained:

TIME (SECONDS)	100 CELL BATTERY VOLTAGE (VOLTS)	FIRST 20 CELL MODULE VOLTAGE (VOLTS)	FIFTH 20 CELL MODULE VOLTAGE (VOLTS)
OCV	174	34	34
5"	143	28.8	30
10"	141	28	29
15"	138	27.5	29
20"	135	26.5	29
30"	127	22	27.5
40"	113	18.5	25.0
50"	100	17.0	21.0

The test was interrupted at t=50 seconds and 20 cc of electrolyte added to the battery. The discharge was continued as follows:

TIME (SECONDS)	100 CELL BATTERY VOLTAGE (VOLTS)	FIRST 20 CELL MODULE VOLTAGE (VOLTS)	FIFTH 20 CELL MODULE VOLTAGE (VOLTS)
OCV	157	31	30
5"	133	27	22.5
10"	121	25.2	17.5
15"	108	24.7	13
20"	99	23.6	10

The results of tests PB021 and PB022 indicate that the present mani-

fold design is adequate. Intercell leakage has been reduced and arcing appears to have been eliminated.

Battery PB023 consisted of twenty 0.3 ampere-hour duplex electrode cells in series. This test was run to determine the effect of longer times of operation on duplex electrode battery performance.

The following parameters apply:

(a) Gasket thickness: 0.020"
(b) Electrolyte inlet feed channel: 1/16" x 0.020" x 1/4"
(c) Silver per electrode: 1.7 grams
(d) Zinc per electrode: 1.05 grams
(e) Duplex electrode thickness: 0.018"
(f) Separator: Pellon #2506K - 3 mils thick.
(g) Activation under pressure using 40 psig nitrogen - helium mixture to displace 20 cc of 38% potassium hydroxide electrolyte.
(h) Battery pack dimensions: 2.42 x 2.675 x 0.54 (3.5 cu. in.)
(i) Battery pack weight: 121.4 grams.

The results obtained were:

Open circuit voltage (5 seconds after activation)	:	36.0 Volts
Discharge rate: 3.5 amps constant current; equivalent to a discharge current density of		1.1 amps per sq. in.
Voltage (after application of load) at 5 seconds	:	29.5 volts
15 seconds	:	29.5 volts
30 seconds	:	29.3 volts
Plateau voltage	:	28.7 volts
Time to 20.0 volts	:	315 seconds
Capacity	:	0.306 Ahr
Watt-hours (based on average voltage)	:	8.8
Battery monobloc energy density	:	2.5 Whrs per cu.in.

We conclude that increasing the time of operation of the twenty (20) cell test module from 75 seconds to 5 minutes did not cause a degradation in performance.

1.1.2.1.2 Design and breadboard of a 1000 cell battery module.

The design of the unit uses the guidelines established in the 100 cell test units described under paragraph 1.1.2.1.1. A total of 2200 unit cell electrodes were prepared and assembled into duplex electrodes. The individual duplexes were then insulated using 0.020 gaskets and made into 28 volt modules.

Parameters for the unit (1500 V nominal load voltage at 3.5 amps) are:

(a) Nominal capacity: 0.5 Ampere-hours

(b) Number of cells: 1000

(c) Number of modules: 50

(d) Number of cells per module: 20

(e) Total duplex electrode thickness: 0.0225" (includes gasket)

(f) Electrode (active material) dimensions: 1-11/16" x 1-15/16"

(g) Active Ag per electrode: 1.7 grams

(h) Active Zn per electrode: 1.1 grams

(i) Available capacity (based upon a silver utilization of 0.33 Ah/g) : 0.56 ampere-hour.

(j) 28 volt module dimensions: 2.45" x 2.65" x 0.48"

(k) Battery monoblock dimensions (not including header): 5.08" x 13.42" x 4.25"

(l) Battery monoblock dimensions (including header): 5.08" x 13.42" x 5.5"

(m) Projected power output: 5.1 KW

(n) Projected energy: 750 Watt-hours

(o) Projected energy density (not including activation system) : 2 Whrs/cu.in.

A drawing of the breadboard battery assembly is presented in Figure 1. Additional sketches showing the details of assembly of the unit cell pack, monoblock, channel feed, and activation hardware are shown in Figures 2, 3, 4, 5, 6, 7, 8, 9.

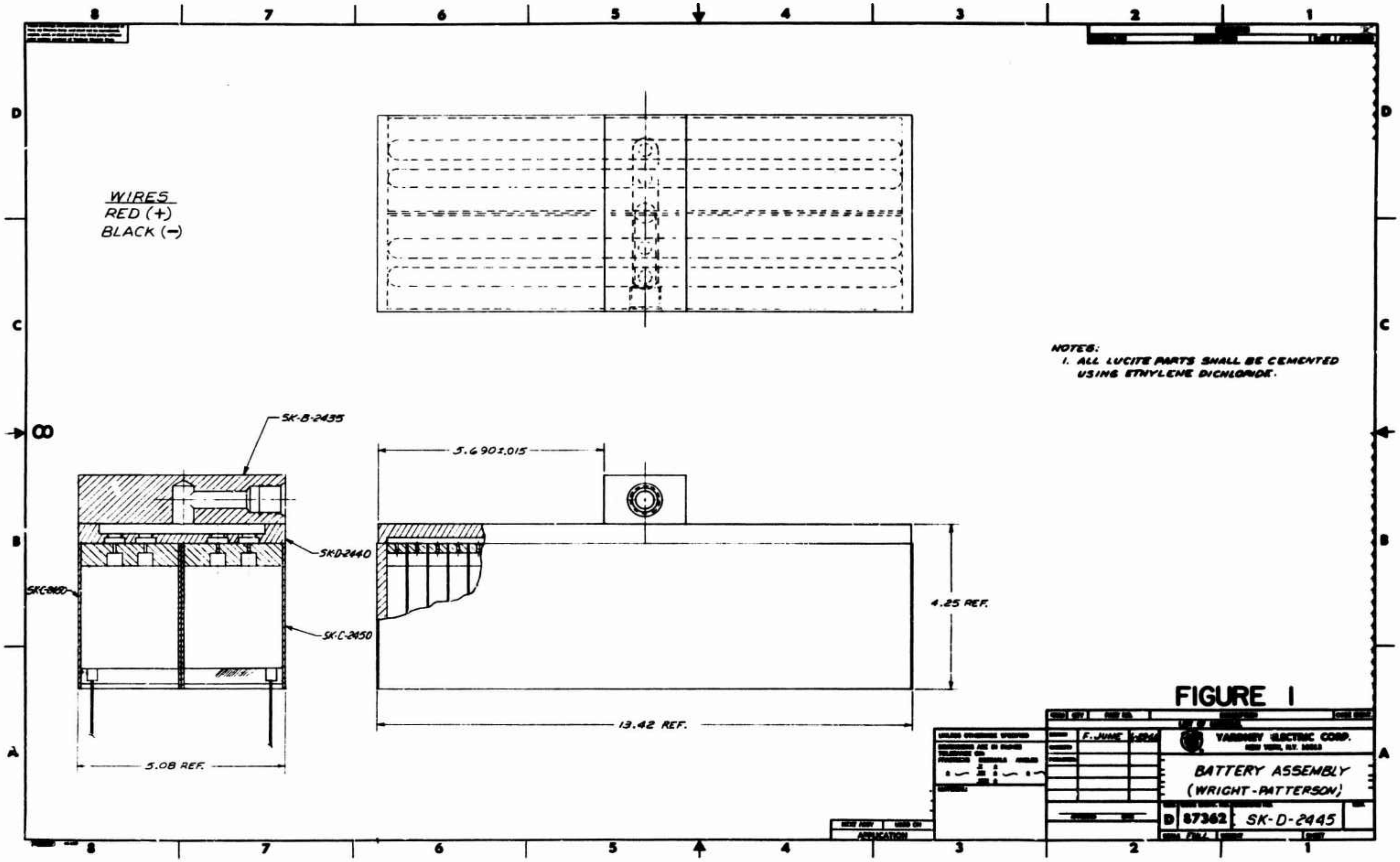
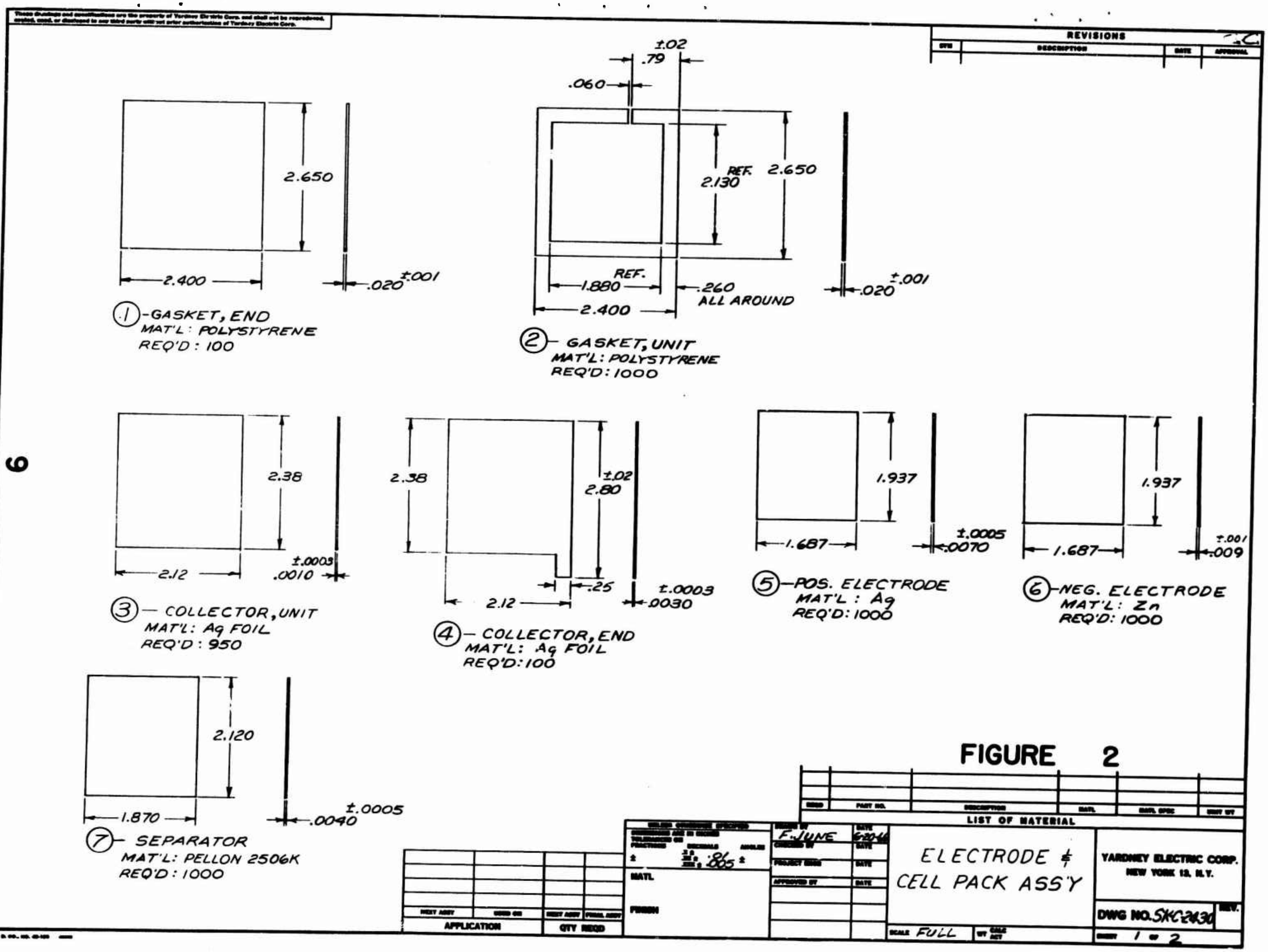

WIRES
RED (+)
BLACK (−)
NOTES:
1. ALL LUCITE PARTS SHALL BE CEMENTED USING ETHYLENE DICHLORIDE.
SK-B-2435
SK-D-2440
SK-C-2450
SK-C-2450
5.690±.015
4.25 REF.
13.42 REF.
5.08 REF.
YARDNEY ELECTRIC CORP.
F. JUNE
BATTERY ASSEMBLY
(WRIGHT-PATTERSON)
D 87362 SK-D-2445
APPLICATION

FIGURE 1



REVISIONS
1 -GASKET, END
MAT'L: POLYSTYRENE
REQ'D: 100
2.650
2.400
.020 ±.001
2 - GASKET, UNIT
MAT'L: POLYSTYRENE
REQ'D: 1000
.060
.79 ±.02
REF. 2.130
2.650
REF. 1.880
2.400
.260 ALL AROUND
.020 ±.001
3 - COLLECTOR, UNIT
MAT'L: Ag FOIL
REQ'D: 950
2.38
2.12
.0010 ±.0003
4 - COLLECTOR, END
MAT'L: Ag FOIL
REQ'D: 100
2.38
2.80 ±.02
.25
2.12
.0030 ±.0003
5 - POS. ELECTRODE
MAT'L: Ag
REQ'D: 1000
1.937
1.687
.0070 ±.0005
6 - NEG. ELECTRODE
MAT'L: Zn
REQ'D: 1000
1.937
1.687
.009 ±.001
7 - SEPARATOR
MAT'L: PELLON 2506K
REQ'D: 1000
2.120
1.870
.0040 ±.0005
LIST OF MATERIAL
F. JUNE
ELECTRODE & CELL PACK ASS'Y
YARDNEY ELECTRIC CORP.
NEW YORK 13, N.Y.
DWG NO. SKC2430
SCALE FULL
SHEET 1 OF 2
APPLICATION
QTY REQD
MATL
FINISH

FIGURE 2

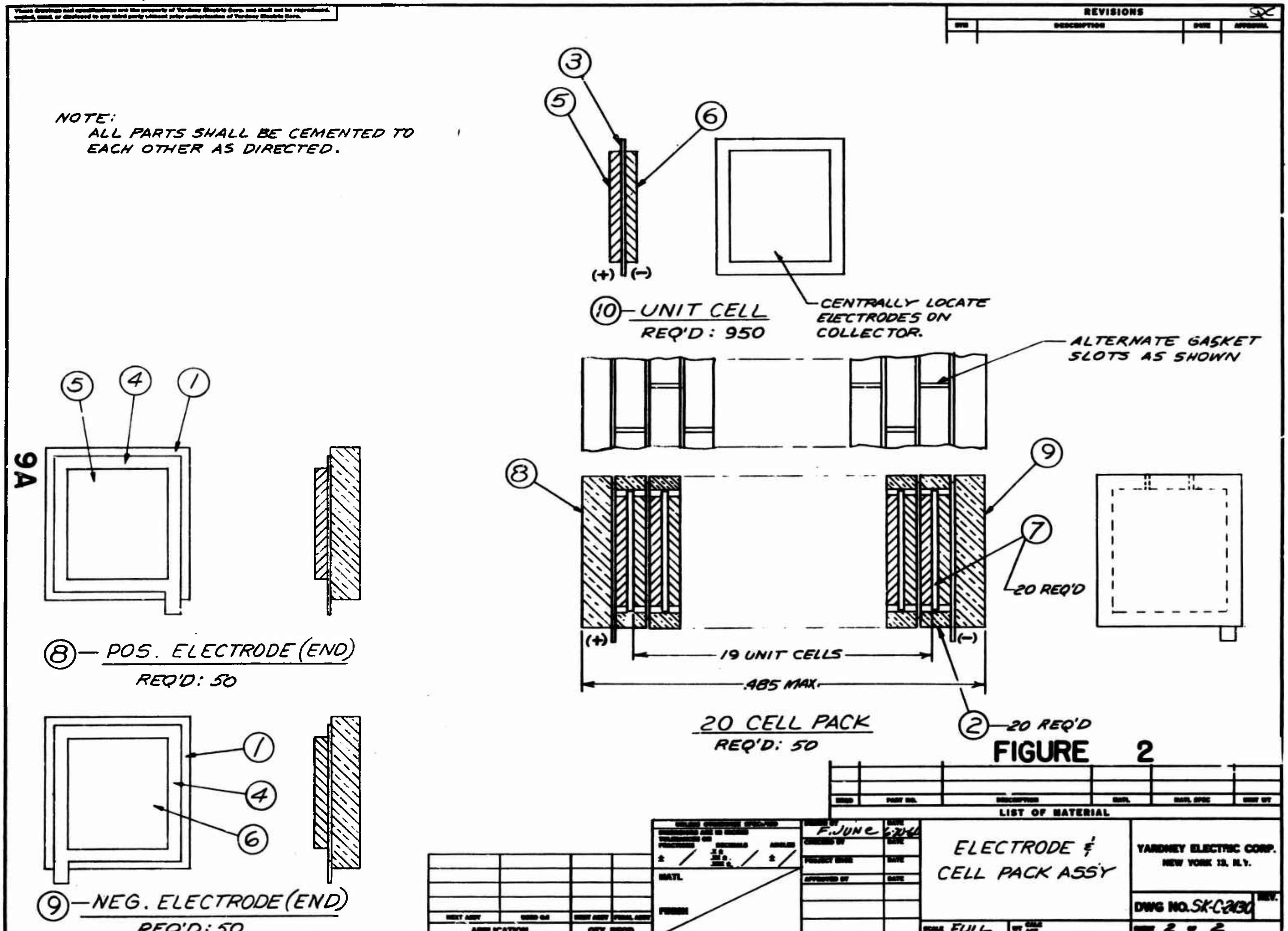
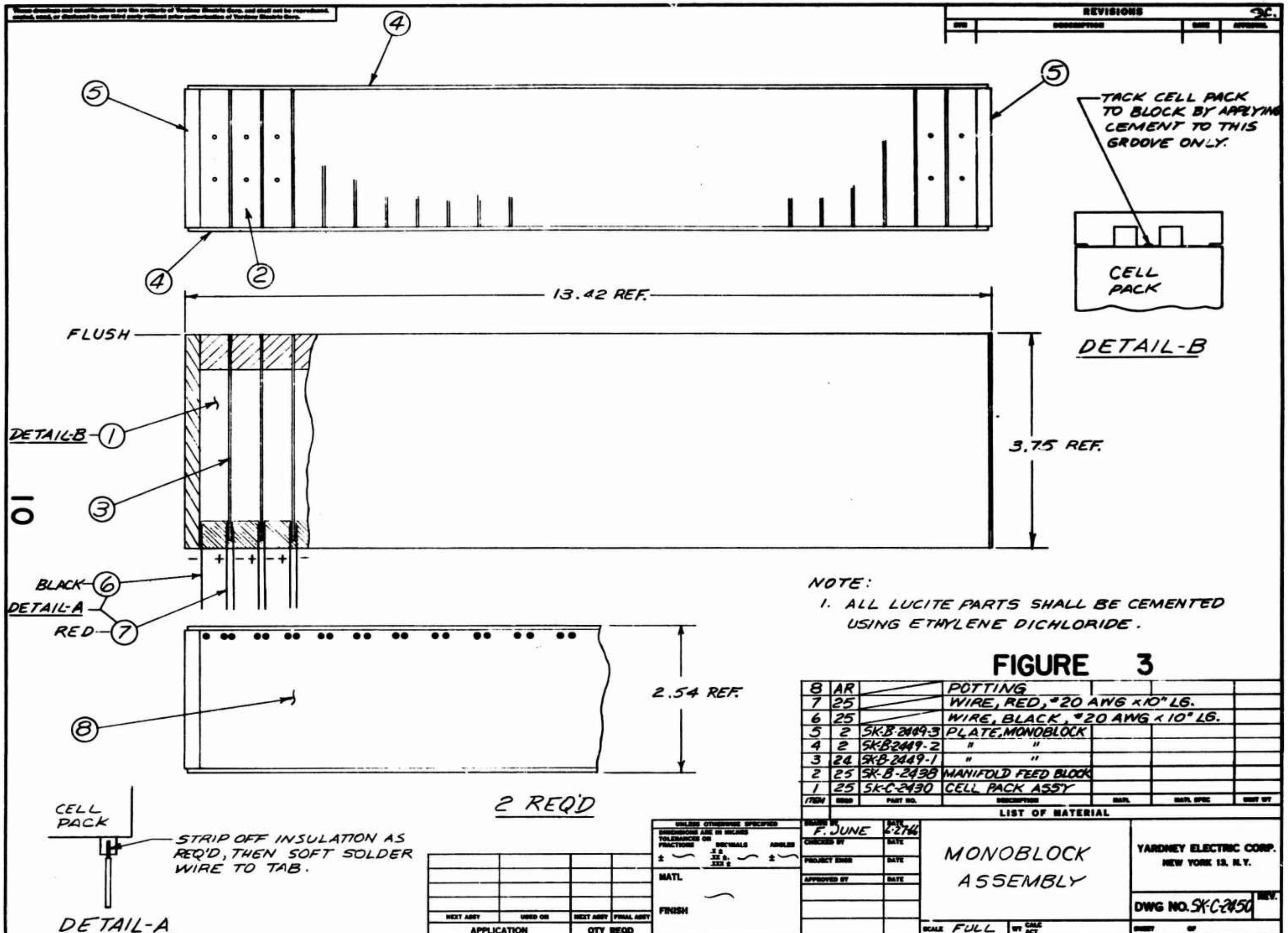

NOTE:
ALL PARTS SHALL BE CEMENTED TO EACH OTHER AS DIRECTED.
REVISIONS
3
5
6
(+)
(−)
10 — UNIT CELL
REQ'D: 950
CENTRALLY LOCATE ELECTRODES ON COLLECTOR.
ALTERNATE GASKET SLOTS AS SHOWN
5
4
1
8
9
7
20 REQ'D
19 UNIT CELLS
.485 MAX.
20 CELL PACK
REQ'D: 50
2 — 20 REQ'D
8 — POS. ELECTRODE (END)
REQ'D: 50
1
4
6
9 — NEG. ELECTRODE (END)
REQ'D: 50
LIST OF MATERIAL
APPLICATION
QTY REQD
MATL
FINISH
F. JUNE
ELECTRODE & CELL PACK ASSY
YARDNEY ELECTRIC CORP.
NEW YORK 13, N.Y.
DWG NO. SK-C2130
SCALE FULL
SHEET 2 OF 2

FIGURE 2



NOTE:
1. ALL LUCITE PARTS SHALL BE CEMENTED USING ETHYLENE DICHLORIDE.

FIGURE 3

ITEM	REQD	PART NO.	DESCRIPTION	MATL	MATL SPEC	UNIT WT
8	AR		POTTING			
7	25		WIRE, RED, #20 AWG × 10" LG.			
6	25		WIRE, BLACK, #20 AWG × 10" LG.			
5	2	SK-B-2449-3	PLATE, MONOBLOCK			
4	2	SK-B-2449-2	" "			
3	24	SK-B-2449-1	" "			
2	25	SK-B-2438	MANIFOLD FEED BLOCK			
1	25	SK-C-2430	CELL PACK ASS'Y			

LIST OF MATERIAL

DRAWN BY F. JUNE DATE 6-27-66

MONOBLOCK ASSEMBLY

YARDNEY ELECTRIC CORP.
NEW YORK 13, N.Y.

DWG NO. SK-C-2450

SCALE FULL

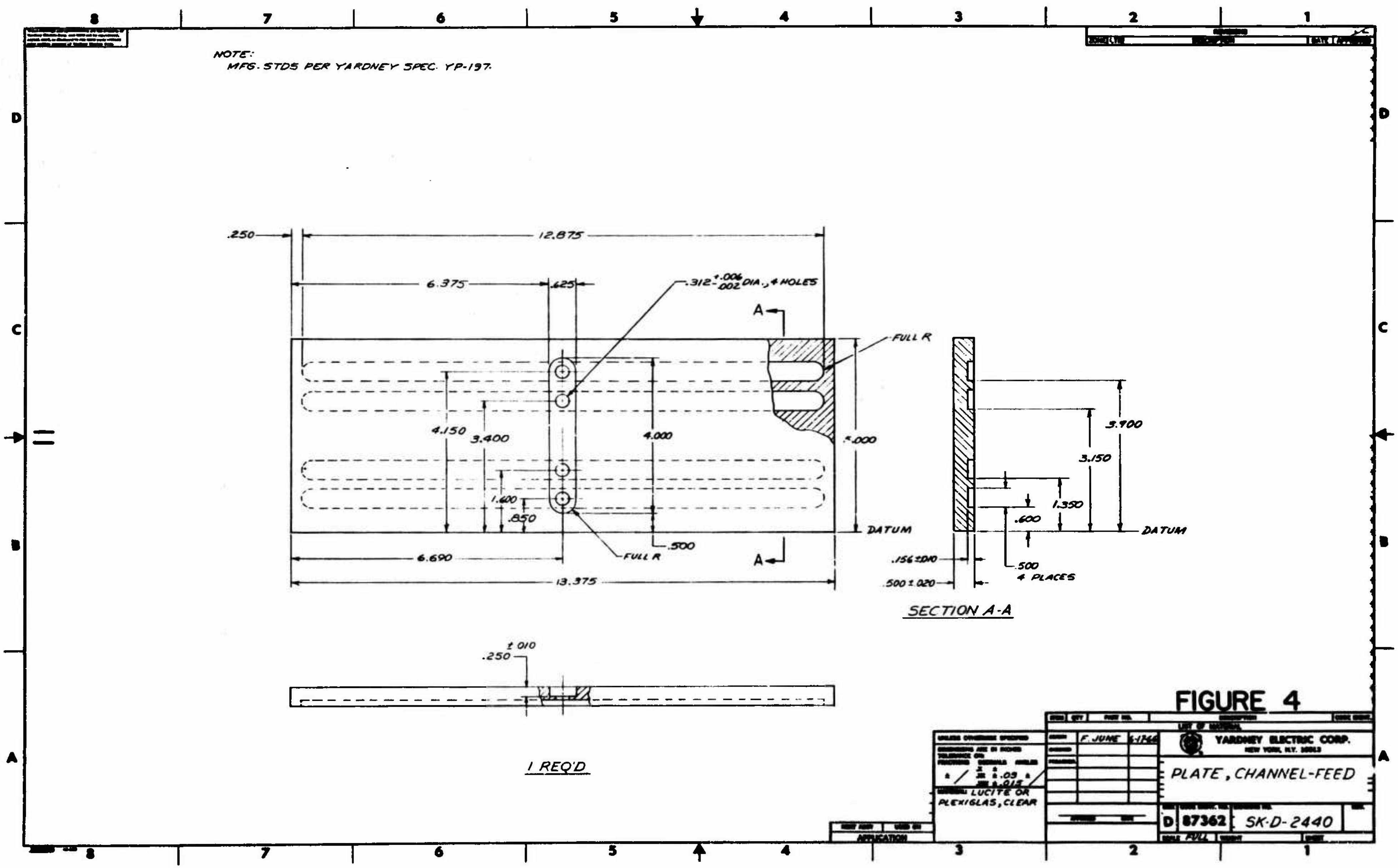

NOTE:
MFG. STDS PER YARDNEY SPEC. YP-197.
.250
12.875
6.375
.625
.312 +.006 -.002 DIA., 4 HOLES
A
FULL R
4.150
3.400
4.000
5.000
1.600
.850
DATUM
.500
FULL R
6.690
13.375
3.900
3.150
1.350
.600
.156±.010
.500±.020
.500
4 PLACES
SECTION A-A
±.010
.250
1 REQ'D
F. JUNE
YARDNEY ELECTRIC CORP.
NEW YORK, N.Y.
PLATE, CHANNEL-FEED
LUCITE OR
PLEXIGLAS, CLEAR
D
87362
SK-D-2440
FULL
APPLICATION

FIGURE 4

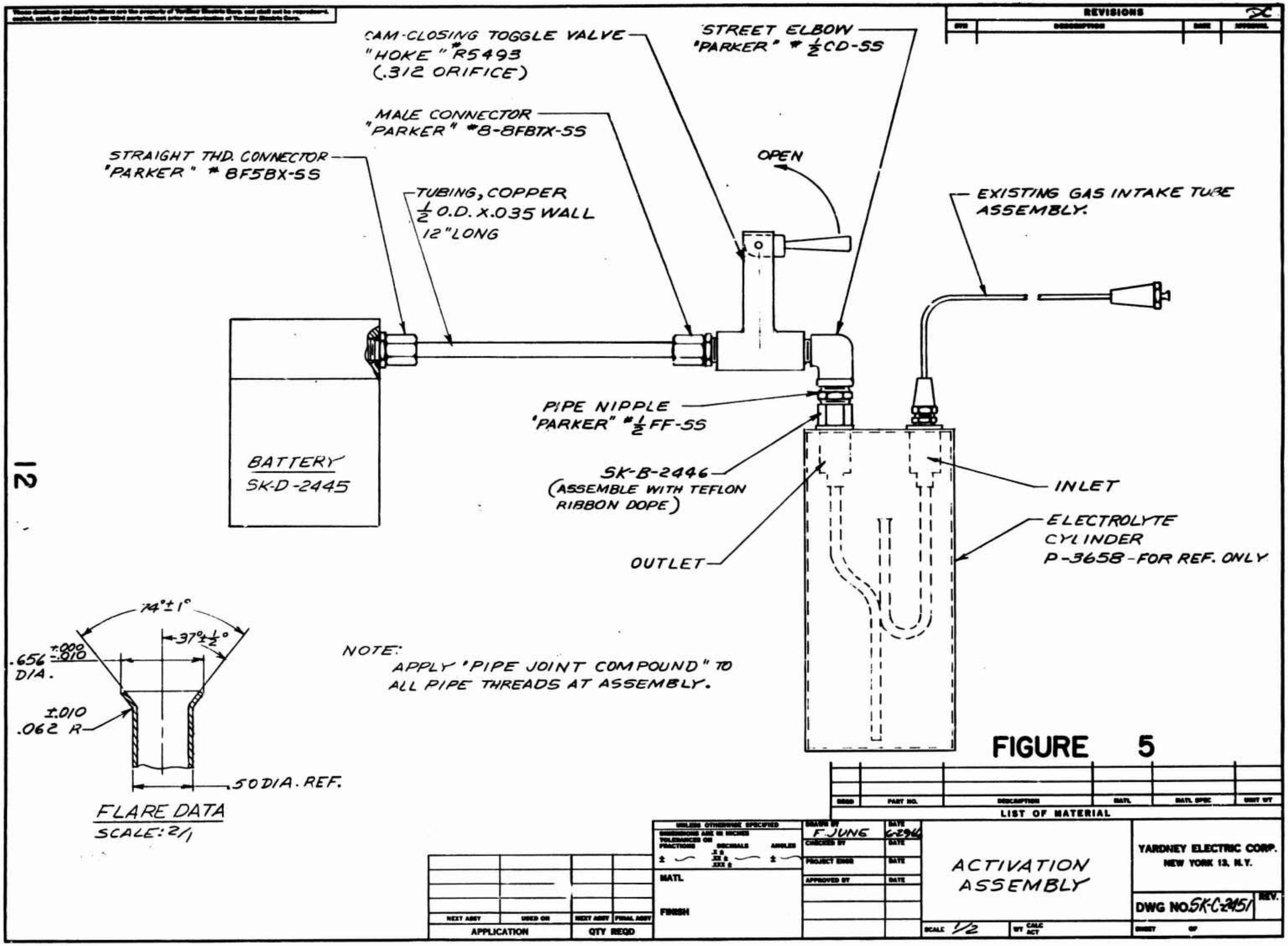

CAM-CLOSING TOGGLE VALVE
"HOKE" #R5493
(.312 ORIFICE)
STREET ELBOW
"PARKER" # 1/2 CD-SS
MALE CONNECTOR
"PARKER" #8-8FBTX-SS
STRAIGHT THD. CONNECTOR
"PARKER" # 8F5BX-SS
TUBING, COPPER
1/2 O.D. X .035 WALL
12" LONG
OPEN
EXISTING GAS INTAKE TUBE
ASSEMBLY.
PIPE NIPPLE
"PARKER" # 1/2 FF-SS
BATTERY
SK-D-2445
SK-B-2446
(ASSEMBLE WITH TEFLON
RIBBON DOPE)
INLET
ELECTROLYTE
CYLINDER
P-3658-FOR REF. ONLY
OUTLET
74°±1°
37°±1/2°
.656 +.000 -.010 DIA.
±.010
.062 R
.50 DIA. REF.
FLARE DATA
SCALE: 2/1
NOTE:
APPLY "PIPE JOINT COMPOUND" TO
ALL PIPE THREADS AT ASSEMBLY.
REVISIONS
LIST OF MATERIAL
DRAWN BY F. JUNG
ACTIVATION
ASSEMBLY
YARDNEY ELECTRIC CORP.
NEW YORK 13, N.Y.
DWG NO. SK-C-2451
SCALE 1/2
APPLICATION
QTY REQD

FIGURE 5

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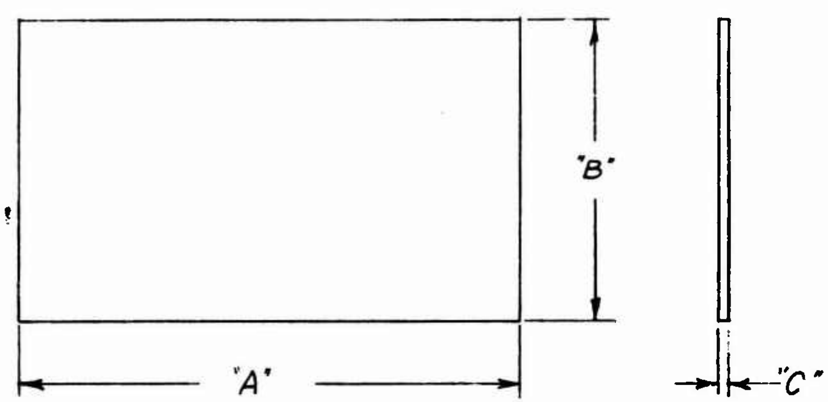
REVISIONS			
SYM	DESCRIPTION	DATE	APPROVAL
			DC



NOTE:
MFG. STDS PER YARDNEY SPEC. YP-197.

PART NO.	DIM "A"	DIM. "B"	DIM. "C"	REQ'D
SK-B-2449-1	$2.410^{\pm.005}$	3.625	$.030^{+.007}_{-.009}$	48
SK-B-2449-2	13.375	3.750	.060±.010	4
SK-B-2449-3	$2.410^{\pm.005}$	3.750	.250±.020	4

FIGURE 6

REQD	PART NO.	DESCRIPTION	MATL	MATL SPEC	UNIT WT

LIST OF MATERIAL

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON FRACTIONS ± / DECIMALS .X ± .XX ± .XXX ± .015 ANGLES ± /

MATL. LUCITE OR PLEXIGLAS,
FINISH CLEAR

DRAWN BY F. JUNE — DATE 6-27-66
CHECKED BY — DATE
PROJECT ENGR — DATE
APPROVED BY — DATE

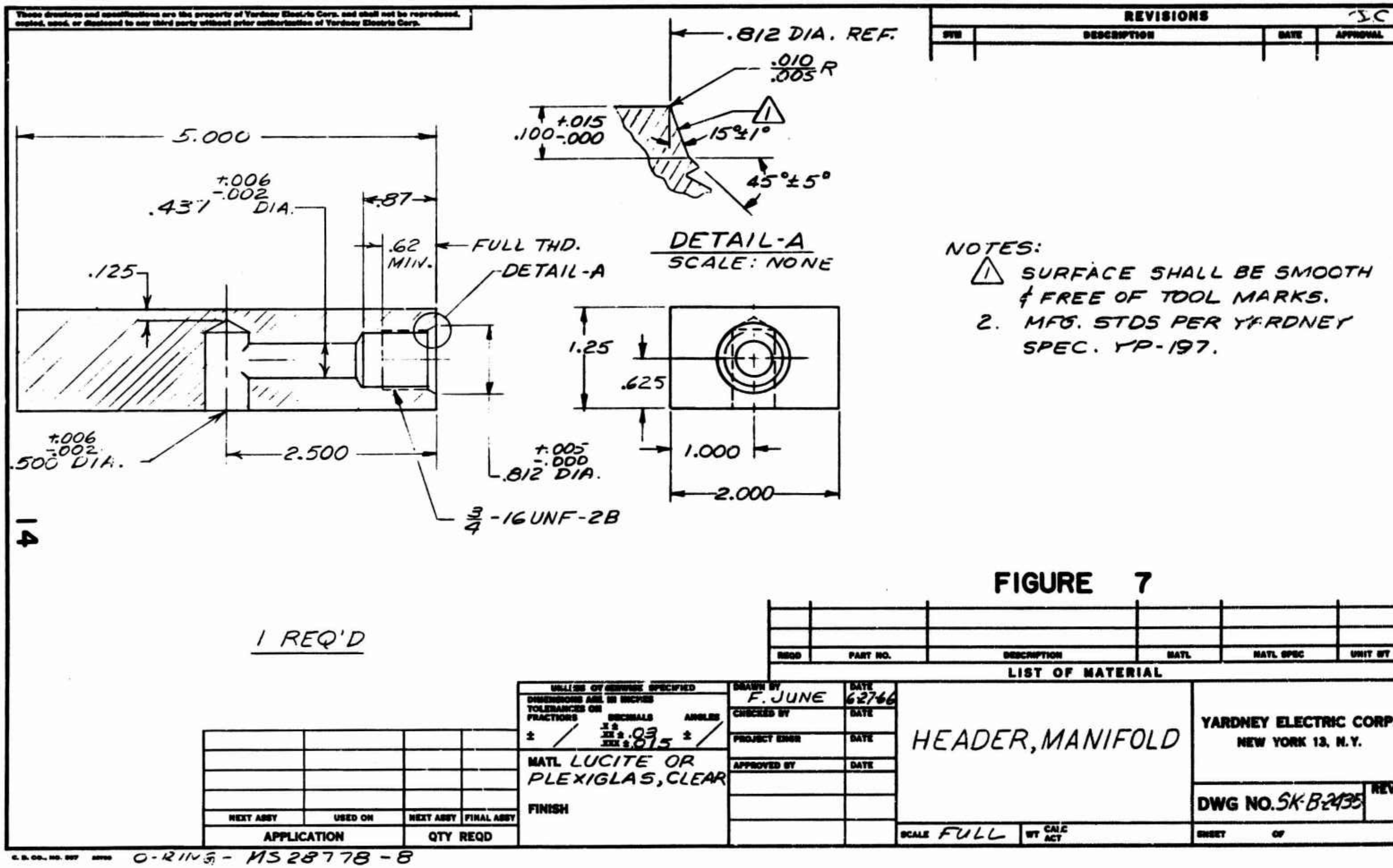
PLATES, MONOBLOCK

YARDNEY ELECTRIC CORP.
NEW YORK 13, N.Y.

DWG NO. SK-B-2449 — REV.

SCALE NONE — WT CALC ACT — SHEET OF

NEXT ASSY	USED ON	NEXT ASSY	FINAL ASSY
APPLICATION		QTY REQD	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REVISIONS
SYM
DESCRIPTION
DATE
APPROVAL
.812 DIA. REF.
.010 .005 R
+.015 -.000 .100
15°±1°
45°±5°
DETAIL-A
SCALE: NONE
5.000
+.006 -.002 .437 DIA.
.87
.62 MIN.
FULL THD.
DETAIL-A
.125
1.25
.625
1.000
2.000
+.006 -.002 .500 DIA.
2.500
+.005 -.000 .812 DIA.
3/4-16UNF-2B
NOTES:
1. SURFACE SHALL BE SMOOTH & FREE OF TOOL MARKS.
2. MFG. STDS PER YARDNEY SPEC. YP-197.
1 REQ'D
REQD
PART NO.
DESCRIPTION
MATL
MATL SPEC
UNIT WT
LIST OF MATERIAL
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON FRACTIONS DECIMALS ANGLES
± / XX ± .03 XXX ± .015 ± /
MATL LUCITE OR PLEXIGLAS, CLEAR
FINISH
DRAWN BY F. JUNE
DATE 6-27-66
CHECKED BY
PROJECT ENGR
APPROVED BY
HEADER, MANIFOLD
YARDNEY ELECTRIC CORP.
NEW YORK 13, N.Y.
DWG NO. SK-B-2435
REV.
SCALE FULL
WT CALC ACT
SHEET OF
NEXT ASSY
USED ON
FINAL ASSY
APPLICATION
QTY REQD
O-RING - MS28778-8

FIGURE 7

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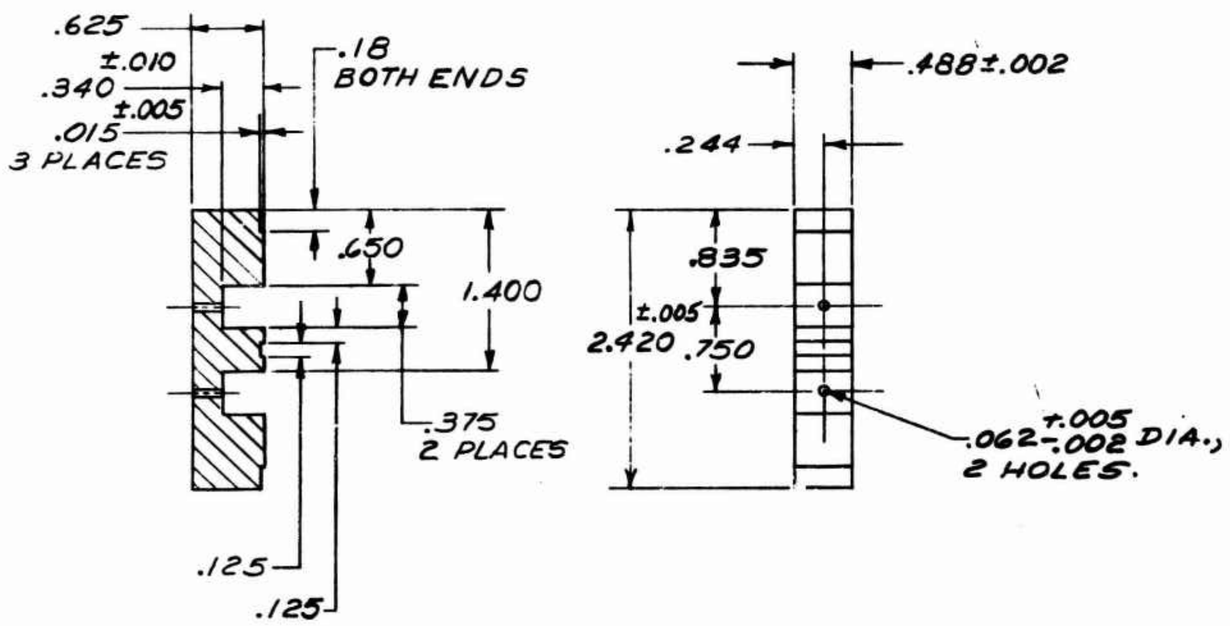
REVISIONS

SYM	DESCRIPTION	DATE	APPROVAL



NOTE:
MFG. STDS PER YARDNEY SPEC. YP-197.

50 REQ'D

FIGURE 8

LIST OF MATERIAL

REQD	PART NO.	DESCRIPTION	MATL	MATL SPEC	UNIT WT

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON FRACTIONS ± / DECIMALS .XX ±.03 .XXX ±.015 ANGLES ± /

MATL LUCITE OR PLEXIGLAS, CLEAR

FINISH

DRAWN BY F. JUNE DATE 6-15-66

CHECKED BY DATE

PROJECT ENGR DATE

APPROVED BY DATE

MANIFOLD FEED BLOCK

YARDNEY ELECTRIC CORP.
NEW YORK 13, N.Y.

DWG NO. SK-B-2438 REV.

SCALE FULL WT CALC ACT SHEET OF

NEXT ASSY	USED ON	NEXT ASSY	FINAL ASSY
APPLICATION		QTY REQD	

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REVISIONS			
SYM	DESCRIPTION	DATE	APPROVAL

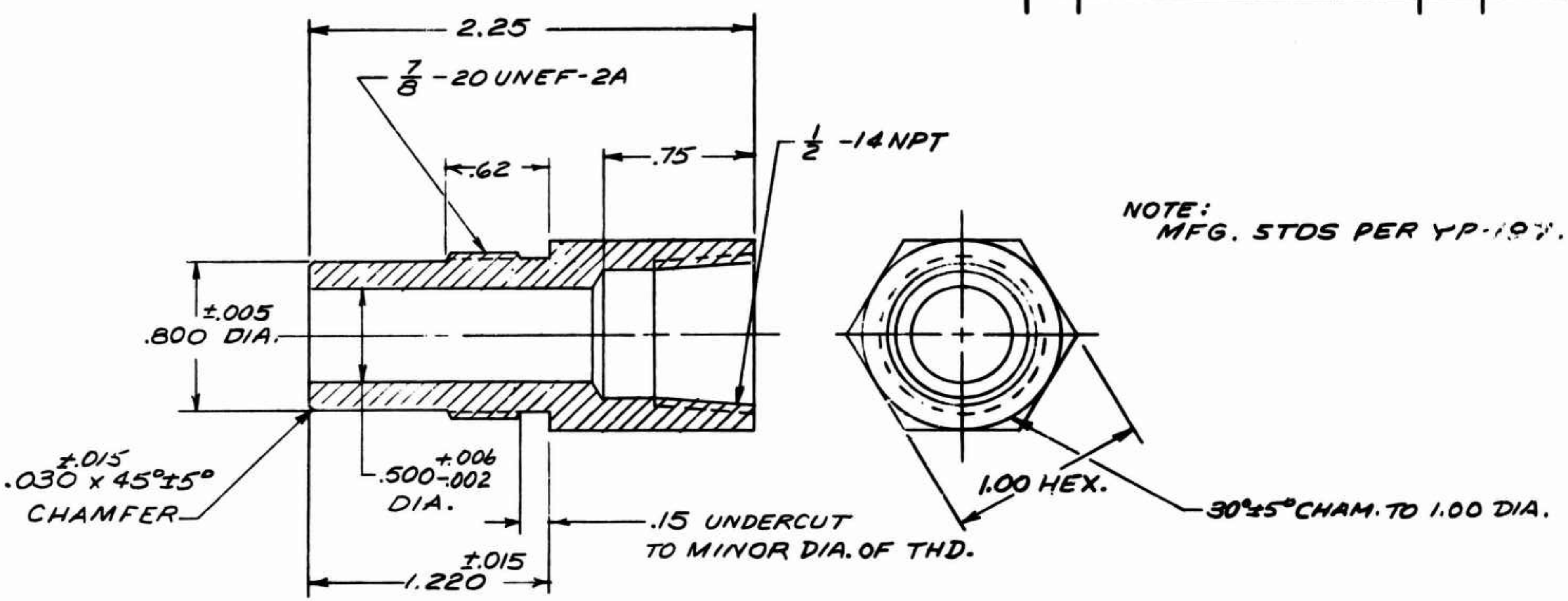


FIGURE 9

REQD	PART NO.	DESCRIPTION	MATL	MATL SPEC	UNIT WT

LIST OF MATERIAL

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON FRACTIONS ± DECIMALS .X ± .XX ± .03 .XXX ± .005 ANGLES ±	
MATL SST, TYPE 303	
FINISH	
DRAWN BY F. JUNE	DATE 6-24-66
CHECKED BY	DATE
PROJECT ENGR	DATE
APPROVED BY	DATE

FITTING, OUTLET

YARDNEY ELECTRIC CORP.
NEW YORK 13, N.Y.

DWG NO. SK-B-2446 REV.

SCALE 2/1 WT CALC ACT SHEET OF

NEXT ASSY	USED ON	NEXT ASSY	FINAL ASSY
APPLICATION		QTY REQD	

Machine plastic parts and other components are being fabricated at the present time. Assembly of the battery is slated for the following work period.

1.1.2.1.2.1 Additional Tests:

Tests run during the last working period include:

(a) Electrical tests on silver and zinc electrode materials prepared for the 1500 V duplex electrode unit.

(b) Electrical tests on finished four cell units representing a sampling of cells from the 1100 unit cells assembled into modules.

1.1.3 The circular duplex electrode battery.

Five (5) alternate design approaches for a circular duplex electrode battery have been established and the projected weight and volume for each approach were calculated. The basic concept is the same for all designs. As previously described, the battery will be activated through the center by means of a central manifold. Each duplex (or cell) is fed through a narrow channel measuring 0.010" x 1/16" x 1/8" which is in registry with a slot connecting modules of twenty cells. This slot, in turn, leads to the main battery activation manifold.

1.1.3.1 Design No. 1

Description: Duplex electrode battery utilizing cells having a circular geometry.

The cells are stacked in a single row and are activated through the center by means of a central manifold feed.

The battery is to be assembled as twenty cell modules.

Battery activation: All-position activation system utilizing a gas generator - electrolyte coil reservoir activation system.

Battery dimensions: 3.375" dia x 26.25" long (233 cubic inches).

1.1.3.2 Design No. 2

Description: Duplex electrode battery utilizing cells having a circular geometry.

The cells are arranged in four stacks. Each stack being activated by means of a central manifold.

The battery is to be assembled as twenty cell modules.

Battery activation: All-position activation system utilizing a gas generator - electrolyte coil reservoir activation system.

Battery dimensions: 6.25" x 6.25" x 6.5" (254 cubic inches).

1.1.3.3 Design No. 3

Description: Duplex electrode battery utilizing cells having a circular geometry.

Cells are arranged in four stacks. Each stack being activated by means of a central manifold.

The battery is to be assembled as twenty cell modules.

One position activation system (gas generator-cylindrical electrolyte tank system.

Battery dimensions: 5.25" x 5.25" x 8.5" (234 cu.in.)

1.1.3.4 Design No. 4

Description: Duplex electrode battery utilizing cells having the shape of a circular sector.

Cells are arranged in four stacks. Central manifold activation.

The battery is to be assembled as twenty cell modules.

All-position activation system (gas generator - electrolyte coil reservoir activation system).

Battery dimensions: 6" dia. x 6.625" (187.5 cu.in).

1.1.3.5 Design No. 5

Description: Duplex electrode battery utilizing cells having the shape of a circular sector.

Cells are arranged in four stacks. Central manifold activation.

The battery is to be assembled as twenty cell modules.

One position activation system. (Gas generator-cylindri-

cal electrolyte tank system).

Battery dimensions: 5" dia. x 8.5" (166.5 cu. in.)

1.1.3.6 As noted previously, the preparation of the duplex electrode, the design of the electrode gasket and the separator material called out are similar to that described for the square cell design except for the form factor. Design verification tests based on 28 volt module test discharges have been scheduled for the next work period.

2.0 The Use of a Battery-Converter System to Supply Power

Work on the study of a battery-converter version of the Missile Power Supply was continued during the last quarter. Essentially, the power supply package consists of a remotely activated silver-zinc primary battery (or batteries) in combination with one or more static power converters.

2.1 The battery section of the battery-converter design approach.

Designs of cell and battery systems for proposed input voltage levels of 5.6, 28, 56, 90 and 200 volts have been prepared for projected battery outputs of 2 kilowatts to 20 kilowatts. Since the battery study was to include conventional (individual) cells as well as duplex electrode (pile type) cells, designs were prepared using both cell types.

Paper designs as well as weights and volumes of cells and battery systems for the proposed input voltages of 5.6, 28, 56, 90 and 200 volts and outputs of 8.5 to 12.1 KW, using conventional (individual) cells have been presented in the third Quarterly Technical Report. From these data, formulae were derived expressing the weight and volume of the batteries as a function of nominal battery terminal voltage, watt-hour rating and percent regulation. The analysis is presented in Appendix III of this report under "Battery Weight and Volume Calculations".

2.1.1 Projected silver-zinc battery energy density versus size and weight as a function of battery voltage (5.6, 28, 56, 90 and 200 volts) and voltage regulations of plus and minus 5, 10 and 15 percent have been determined for batteries utilizing the pile type (duplex electrode) construction, in the range of 133 to 190 watt-hours. For purposes of optimization, the units were designed with the thinnest possible spacer gaskets (0.010" thick). Tabulated data are presented in Table I to show the effect of reducing the duplex electrode gasket thickness from 0.020" to 0.010".

2.1.2 Optimized weight and volume projections for battery systems (utilizing conventional cells as well as duplex electrodes) with outputs of 2 KW and 20 KW and operating times of 15 seconds and 5 minutes have been

TABLE I

BATTERY TYPE	VOLTAGE	WEIGHT (lbs.)	VOLUME (in^3)	CURRENT DENSITY A/in^2	ASSUMED CONVERTER EFF.	WATT-HRS. OUTPUT	REMARKS
CONVENTIONAL CELL (4.75AH)	90V ± 10%	5.3	107	1.5	100	133	INDIVIDUAL CELL CONSTRUCTION
DUPLEX ELECTRODE (4.75 AH)	90V ± 10%	11.9	225	1.5	100	133	GASKET THICK. = 0.020" 7 PAR. SECTIONS
DUPLEX ELECTRODE (4.75 AH)	90V ± 10%	7.55	95.5	1.5	100	133	GASKET THICK. = 0.010" 7 PAR. SECTIONS
DUPLEX ELECTRODE (4.75 AH)	90V ± 10%	5.72	129	1.5	100	133	GASKET THICK. = 0.010" SINGLE SECTION

TABLE I
(Continued)

BATTERY TYPE	VOLTAGE	WEIGHT (lbs.)	VOLUME (in3)	CURRENT DENSITY A/in^2	ASSUMED CONVERTER EFF.	WATT-HRS. OUTPUT	REMARKS
CONVENTIONAL CELL (0.67 AH)	200V ±10%	5.9	137	1.5	100	133	INDIVIDUAL CELL CONSTRUCTION
DUPLEX ELECTRODE (0.67 AH)	200V ±10%	9.1	208	1.5	100	133	GASKET THICK. = 0.020" 7 PAR. SECTIONS
DUPLEX ELECTRODE (0.67 AH)	200V ±10%	6.76	85	1.5	100	133	GASKET THICK. = 0.010" 7 PAR. SECTIONS
DUPLEX ELECTRODE (0.67 AH)	200V ±10%	5.4	88.6	1.5	100	133	GASKET THICK. = 0.010" SINGLE SECTION

compiled in Table II. The methodology and sample calculations for these projections were presented in the Third Quarterly Progress Report.

Summary sheets showing (a) battery component volumes versus battery voltage (b) battery component weights versus battery voltage (c) overall battery volumes versus battery voltage (d) overall battery weights versus battery voltage as a function of output (watt-hours) and voltage regulation, are presented in Appendix I. Energy density figures have also been calculated for each of the battery types.

2.1.3 Design verification of the projected design for a 90 volt 133 watt-hr. conventional cell battery.

As discussed previously (3rd. Quarterly Progress Report), the battery consists of 64 cells (nominal capacity: 1.48 ampere-hours) in series and is designed to operate at a voltage regulation of plus or minus five percent.

The energy density of the battery was calculated as 23 watt-hours per pound and 1.16 watt-hours per cubic inch.

A design layout of the proposed battery was prepared in order to verify the overall battery dimensions previously calculated.

A print of the layout drawing has been reproduced in Figure 10.

The projected volume of the unit (w/o outer case) had formerly been established as 125 cubic inches. The actual volume (including the outer case), in accordance with the design layout, is determined to be 141 cubic inches, indicating a good correlation between the predicted and the design established values.

2.2 The converter section of the power supply.

The subcontract for the study and optimization phase of a DC to DC converter for the Missile Power Supply was awarded to the Ordnance Division of Honeywell Inc., during the last reporting period. Work was initiated on phase I of the program on April 15, 1966.

2.2.1 A technical program plan outlining the projected work on the converter was submitted to Yardney Electric by Honeywell. A copy of this document has been included in Appendix II of this report.

2.2.2 Honeywell's first quarterly progress report which documents the effort expended during the preceding three months of this study program will be found in Appendix III of this report.

TABLE II - Battery-Converter Study
Battery Parameters for 2 Kilowatt and 20 Kilowatt Output Requirements (Conventional Cells)

BATTERY VOLTAGE (VOLTS)	REQUIRED POWER OUTPUT (KW)	TIME	REQUIRED ENERGY OUTPUT (WHRS)	MAXIMUM CURRENT (AMPS)	CAPACITY (AH)
5.6	2	15"	8.33	357	1.49
	2	5'	167	357	29.7
	20	15"	83.3	3570	14.9
	20	5'	1670	3570	29.7
28	2	15"	8.33	71.4	0.298
	2	5'	167	71.4	5.95
	20	15"	83.3	714	2.98
	20	5'	1670	714	59.5
56	2	15"	8.33	35.7	0.149
	2	5'	167	35.7	2.97
	20	15"	83.3	357	1.49
	20	5'	1670	357	29.7
90	2	15"	8.33	22.2	0.0926
	2	5'	167	22.2	1.85
	20	15"	83.33	222	0.926
	20	5'	1670	222	18.5
200	2	15"	8.33	10	0.0417
	2	5'	167	10	0.833
	20	15"	83.3	100	0.417
	20	5'	1670	100	8.33

TABLE II (Continued)

CONVENTIONAL CELL - BATTERY OUTPUT : 83.3 WATT-HOURS AT 20 KILOWATTS

Battery Voltage	5.6 Volts			28 Volts			56 Volts			90 Volts			200 Volts		
No. of Cells	4	4	4	20	20	20	40	39	39	64	63	63	143	140	137
Capacity (AH)		14.9			2.98			1.49			0.926			0.417	
Voltage Regulation	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%
Overall Unit Cell Weight (Grams)	623	516	440	128	106	91.7	65.0	55.1	46.6	41.9	35.3	30.3	21.6	18.2	16.8
Unit Cell Volume (in^3)	22.4	17.5	13.9	4.87	3.80	3.15	2.62	2.15	1.75	1.80	1.49	1.25	1.08	0.93	0.84
Monoblock Weight (Grams)	2490	2060	1760	2560	2130	1830	2600	2140	1810	2680	2220	1910	3100	2540	2300
Monoblock Volume (in^3)	89.5	68.3	54.8	935	71.3	59.0	96.2	75.7	60.2	101	80.4	65.3	123	99	85.8
Total Electrolyte Weight (Grams)	776	588	452	778	574	452	765	578	432	770	573	430	802	583	468
Total Electrolyte Volume (in^3)	34.4	26	20.0	34.4	25.4	20.0	34	25.1	19.1	34.1	25.3	19.0	35.5	25.7	20.7
Active Material Weight (Grams)	387	387	387	387	387	387	387	377	377	385	378	378	388	380	372
Active Material Volume (in^3)	7.54	7.54	7.54	7.54	7.54	7.54	7.54	7.34	7.34	7.54	7.34	7.34	7.54	7.39	7.25
Electrolyte Coil Length (inches)	190	144	110	190	140	110	188	141	106	188	140	105	196	142	114
Weight (Grams)	370	280	216	370	274	216	366	274	206	367	273	205	382	277	222
Overall Battery															
Length (inches)	8.80	6.85	5.59	9.18	7.12	5.98	9.44	7.54	6.10	9.92	7.97	6.57	11.9	9.72	8.47
Volume (in^3)	153	119	97	159	123	104	164	131	106	172	138	114	206	169	147
Weight (Grams)	3740	3030	2530	3810	3030	2600	3830	3090	2550	4060	3170	2650	4380	3500	3090
Weight (lbs)	8.22	6.67	5.57	8.40	6.67	5.72	8.43	6.80	5.62	8.94	6.98	5.84	9.65	7.70	6.80
Watt-Hours/lb	10.1	12.5	15.0	9.90	12.5	14.5	9.90	12.2	14.8	9.3	11.9	14.3	8.6	10.8	12.2
Watt-Hours/in^3	0.545	0.70	0.86	0.523	0.676	0.80	0.508	0.635	0.785	0.485	0.603	0.73	0.404	0.493	0.566

TABLE II (Continued)

CONVENTIONAL CELLS - BATTERY OUTPUT : 8.33 WATT-HOURS AT 2 KILOWATTS

Battery Voltage		5.6 Volts			28 Volts			56 Volts			90 Volts			200 Volts	
No. of Cells	4	4	4	20	20	19	39	39	37	63	64	60	139	130	124
Capacity (AH)		1.49			0.298			0.149			0.0926			0.0417	
Voltage Regulation	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%
Overall Unit Cell Weight (Grams)	64.9	55.1	46.6	16.5	15.1	13.6	10.8	9.49	9.49	8.44	6.85	6.85	6.08	6.08	6.08
Unit Cell Volume (in^3)	2.62	1.94	1.76	0.89	0.82	0.74	0.70	0.63	0.63	0.61	0.55	0.55	0.53	0.53	0.53
Monoblock Weight (Grams)	260	220	186	330	301	258	423	370	351	532	438	411	845	790	755
Monoblock Volume (in^3)	9.84	7.1	6.37	13.8	12.3	10.2	19.0	16.3	15.6	25.3	21.3	20.0	43.6	40.8	38.9
Total Electrolyte Weight (Grams)	76.5	58.8	44.0	81	66	48.7	94	65.5	62.2	103	58	54	116	108	103
Total Electrolyte Volume (in^3)	3.4	2.61	1.96	3.58	2.92	2.16	4.14	2.90	2.75	4.54	2.56	2.40	5.15	4.82	4.59
Active Material Weight (Grams)	38.7	38.7	38.7	38.7	38.7	36.7	37.7	37.7	35.8	37.8	38.3	36.0	37.7	35.2	33.6
Active Material Volume (in^3)	0.75	0.75	0.75	0.75	0.75	0.71	0.73	0.73	0.70	0.74	0.75	0.70	0.73	0.69	0.65
Electrolyte Coil															
Length (inches)	18.8	14.4	10.9	19.8	16.1	11.9	22.8	16	15.2	25	14.2	13.3	28.5	26.6	25.4
Weight (Grams)	36.7	28	21.2	38.6	31.4	23.2	44.5	31.2	29.6	48.8	27.7	25.8	55.5	51.9	49.5
Overall Battery															
Length (inches)	1.41	1.16	1.09	1.78	1.64	1.45	2.27	2.02	1.95	2.85	2.48	2.36	4.55	4.29	4.12
Volume (in^3)	24.6	20.1	18.9	31	28.4	25.1	39.4	35.0	33.8	49.5	43	41	79	74.5	71.5
Weight (Grams)	474	407	351	550	498	430	662	567	543	784	624	591	1120	1050	1010
Weight (lbs)	1.04	0.895	0.772	1.21	1.10	0.946	1.46	1.25	1.20	1.75	1.37	1.30	2.47	2.31	2.22
Watt-Hours/lb	8.0	9.3	10.8	6.9	7.55	8.80	5.70	6.65	6.95	4.76	6.07	6.40	3.37	3.60	3.75
Watt-Hours/in^3	0.34	0.41	0.44	0.268	0.293	0.331	0.201	0.238	0.246	0.168	0.194	0.203	0.105	0.112	0.117

TABLE II (Continued)

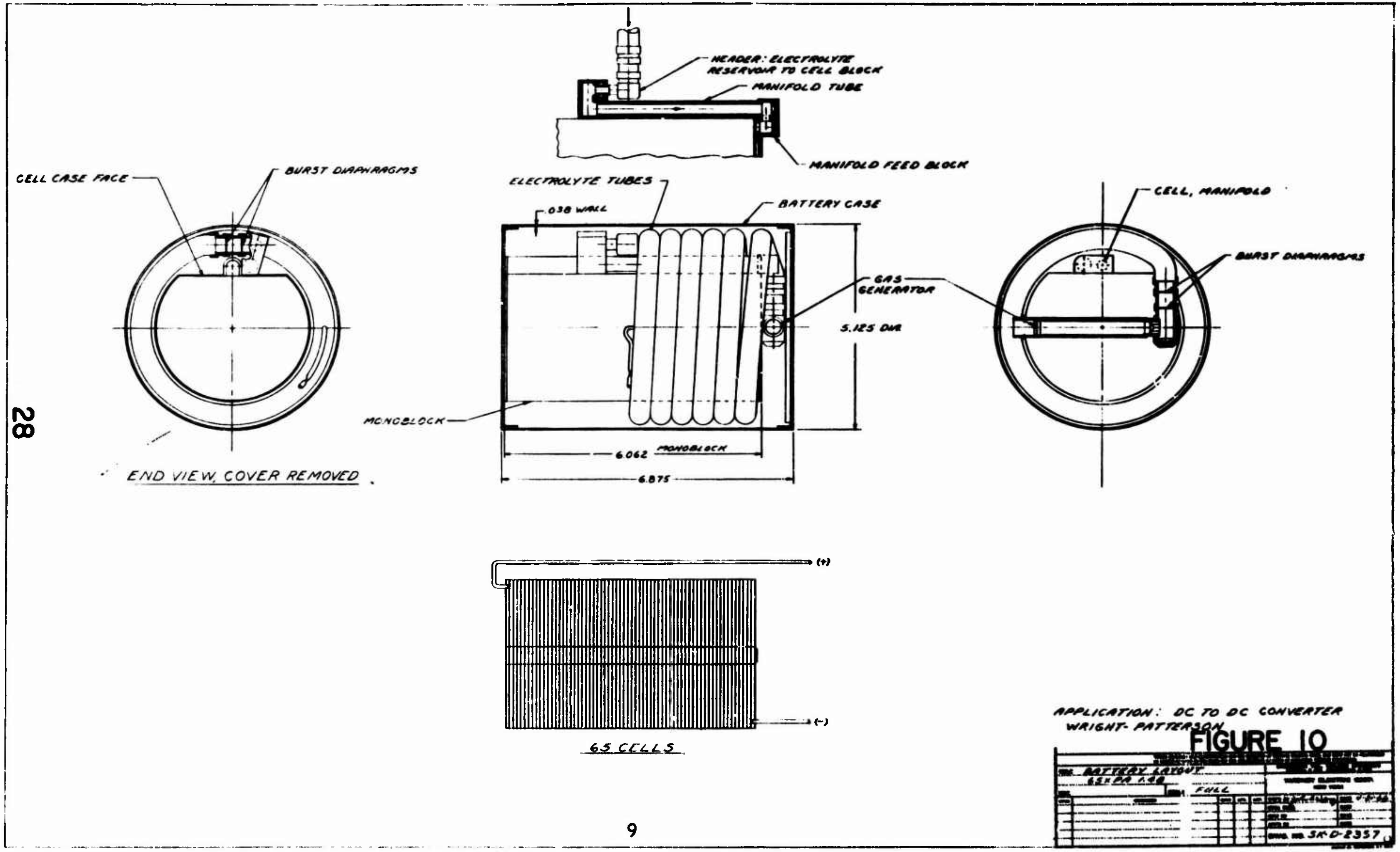
CONVENTIONAL CELL - BATTERY OUTPUT : 167 WATT-HOURS AT 2 KILOWATTS

Battery Voltage	5.6 Volts			28 Volts			56 Volts			90 Volts			200 Volts		
No. of Cells	4	4	4	20	20	19	39	39	37	63	64	60	139	130	124
Capacity (AH)		29.7			5.95			2.97			1.85			0.833	
Voltage Regulation	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%
Overall Unit Cell Weight (Grams)	275	265	257	58.8	57.4	56	32.4	30.8	30.8	21.9	20.3	20.3	12.5	12.5	12.5
Unit Cell Volume (in^3)	8.50	8.12	7.77	2.18	2.14	2.12	1.39	1.37	1.37	1.08	1.11	1.11	0.79	0.79	0.79
Monoblock Weight (Grams)	1100	1060	1030	1180	1150	1060	1260	1200	1140	1380	1290	1210	1740	1620	1550
Monoblock Volume (in^3)	34.0	31.8	30.3	39.6	38.8	36.4	46	45.2	43.0	54.5	57.5	53.9	80.3	74.5	71.0
Total Electrolyte Weight (Grams)	177	170	155	200	189	170	218	191	181	236	226	212	278	261	250
Total Electrolyte Volume (in^3)	7.85	7.52	6.9	8.9	8.36	7.55	9.7	8.4	8.0	10.4	10.0	9.36	12.4	11.5	11.0
Active Material Weight (Grams)	773	773	773	774	774	735	753	753	715	756	768	721	754	704	671
Active Material Volume (in^3)	15.0	15.0	15.0	15.1	15.0	14.3	14.7	14.7	14.0	14.7	15.0	14.0	14.6	13.7	13.1
Electrolyte Coil Length (inches)	43.3	41.5	38.1	49.1	46.2	41.7	53.5	46.5	44.2	57.5	55	51.8	68.5	63.6	61
Weight (Grams)	84.5	81	74.4	95.5	90	81.2	104	90.8	86.0	112	107	101	133	124	119
Overall Battery Length (inches)	3.66	3.46	3.32	4.18	4.10	3.88	4.77	4.70	4.50	5.56	5.84	5.5	7.94	7.42	7.09
Volume (in^3)	63.5	60.0	57.6	72.5	71.2	67.3	83	81.6	78	96.5	101	95.5	138	129	123
Weight (Grams)	1460	1410	1360	1575	1530	1410	1680	1580	1470	1830	1720	1625	2250	2105	2020
Weight (Lbs.)	3.22	3.10	3.0	3.47	3.37	3.10	3.7	3.48	3.24	4.02	3.79	3.58	4.95	4.64	4.45
Watt-Hours/lb.	51.9	53.8	55.7	48.1	49.5	53.8	45.2	48.0	51.6	41.5	44.1	46.7	33.8	36.0	37.5
Watt-Hours/in^3	2.63	2.78	2.90	2.30	2.35	2.48	2.01	2.05	2.14	1.73	1.65	1.75	1.21	1.30	1.36

TABLE II (Continued)

CONVENTIONAL CELL - BATTERY OUTPUT : 1670 WATT-HOURS AT 20 KILOWATTS

Battery Voltage		5.6 Volts			28 Volts			56 Volts			90 Volts			200 Volts	
No. of Cells	4	4	4	20	20	20	40	39	39	64	63	62	143	140	137
Capacity (AH)		297			59.5			29.7			18.5			8.33	
Voltage Regulation	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%	±5%	±10%	±15%
Overall Unit Cell Weight (Grams)	2723	2615	2540	548	527	512	275	265	257	173	166	161	80.5	77.0	76
Unit Cell Volume (in^3)	80	75.5	71.7	16.5	15.6	15.0	8.5	8.1	7.77	5.53	5.28	5.1	2.82	2.72	2.69
Monoblock Weight (Grams)	10,900	10,400	10,160	10,960	10,500	10,240	11,000	10,300	10,000	11,100	10,500	10,000	11,600	10,800	10,400
Monoblock Volume (in^3)	318	301	286	327	308	295	332	308	294	336	319	303	372	351	339
Total Electrolyte Weight (Grams)	1840	1670	1530	1870	1690	1550	1880	1650	1520	1870	1680	1540	1970	1750	1640
Total Electrolyte Volume (in^3)	81.6	74	67.7	82.6	74.8	68.8	82.5	73.4	67.2	83.2	74.5	68.3	87.3	77.8	73.0
Active Material Weight (Grams)	7730	7730	7730	7740	7740	7740	7730	7550	7550	7690	7590	7450	7740	7570	7420
Active Material Volume (in^3)	150	150	150	150	150	150	150	147	147	150	148	145	150	147	144
Electrolyte Coil															
Length (inches)	450	408	374	455	413	380	455	405	371	460	412	377	482	430	403
Weight (Grams)	880	796	730	890	805	742	890	790	725	900	803	735	945	838	786
Overall Battery															
Length (inches)	30.1	28.5	27.1	30.9	29.1	27.9	31.3	29.1	27.8	31.8	30.1	28.7	35.1	33.1	32.0
Volume (in^3)	523	495	470	535	505	485	543	505	482	552	523	498	610	575	555
Weight (Grams)	13,720	12,970	12,520	13,820	13,100	12,630	13,770	12,840	12,350	13,970	13,080	12,375	14,615	13,490	12,930
Weight (lbs)	30.2	28.6	27.6	30.4	28.9	27.8	30.4	28.3	27.2	30.8	28.8	27.3	32.2	29.7	28.5
Watt-Hours/lb	55.3	58.4	60.5	55.0	57.8	60.1	55.0	59.0	61.4	54.3	58.0	61.2	51.9	56.2	58.6
Watt-Hours/in^3	3.19	3.38	3.56	3.12	3.31	3.44	3.08	3.31	3.47	3.03	3.20	3.36	2.74	2.90	3.01


HEADER: ELECTROLYTE RESERVOIR TO CELL BLOCK
MANIFOLD TUBE
MANIFOLD FEED BLOCK
CELL CASE FACE
BURST DIAPHRAGMS
ELECTROLYTE TUBES
.038 WALL
BATTERY CASE
GAS GENERATOR
5.125 DIA
CELL, MANIFOLD
BURST DIAPHRAGMS
MONOBLOCK
6.062 MONOBLOCK
6.875
END VIEW, COVER REMOVED
(+)
(-)
65 CELLS
APPLICATION: DC TO DC CONVERTER
WRIGHT-PATTERSON
BATTERY LAYOUT
65 x PA 1.48
FULL
SK-D-2357
9
FIGURE 10

III CONCLUSIONS

1. It has been established that a duplex electrode battery power supply utilizing a square configuration will weigh 13.7 lbs. in a volume of 266 cubic inches.

2. Analysis of the design of a duplex electrode battery power supply utilizing a circular configuration has indicated that a unit can be developed that will occupy a volume as low as 166.5 cubic inches.

3. A test run on a twenty cell duplex electrode battery to determine the effect of longer times of operation (up to 5 minutes) on duplex electrode performance has shown that the increase in time of discharge did not cause a degradation in performance.

4. Tests have shown that the arcing and intercell leakage usually associated with high density packaging of high voltage duplex electrode batteries can be minimized, if not eliminated, by subdividing the battery package into twenty cell modules, each module being activated through separate manifold channels.

5. A breadboard 1500 volt experimental duplex electrode battery has been designed. Projected power output is 5.1 KW and projected energy of the unit: 750 watt-hours. Overall battery assembly dimensions will be 5.08" x 13.42" x 5.5".

6. Various combinations of batteries and converter regulators were investigated and evaluated under the work program subcontracted to Honeywell, Inc.

   A design methodology for the battery-converter approach is being developed, to be applicable to similar systems of various power levels, voltage levels and load transfer durations.

APPENDIX I

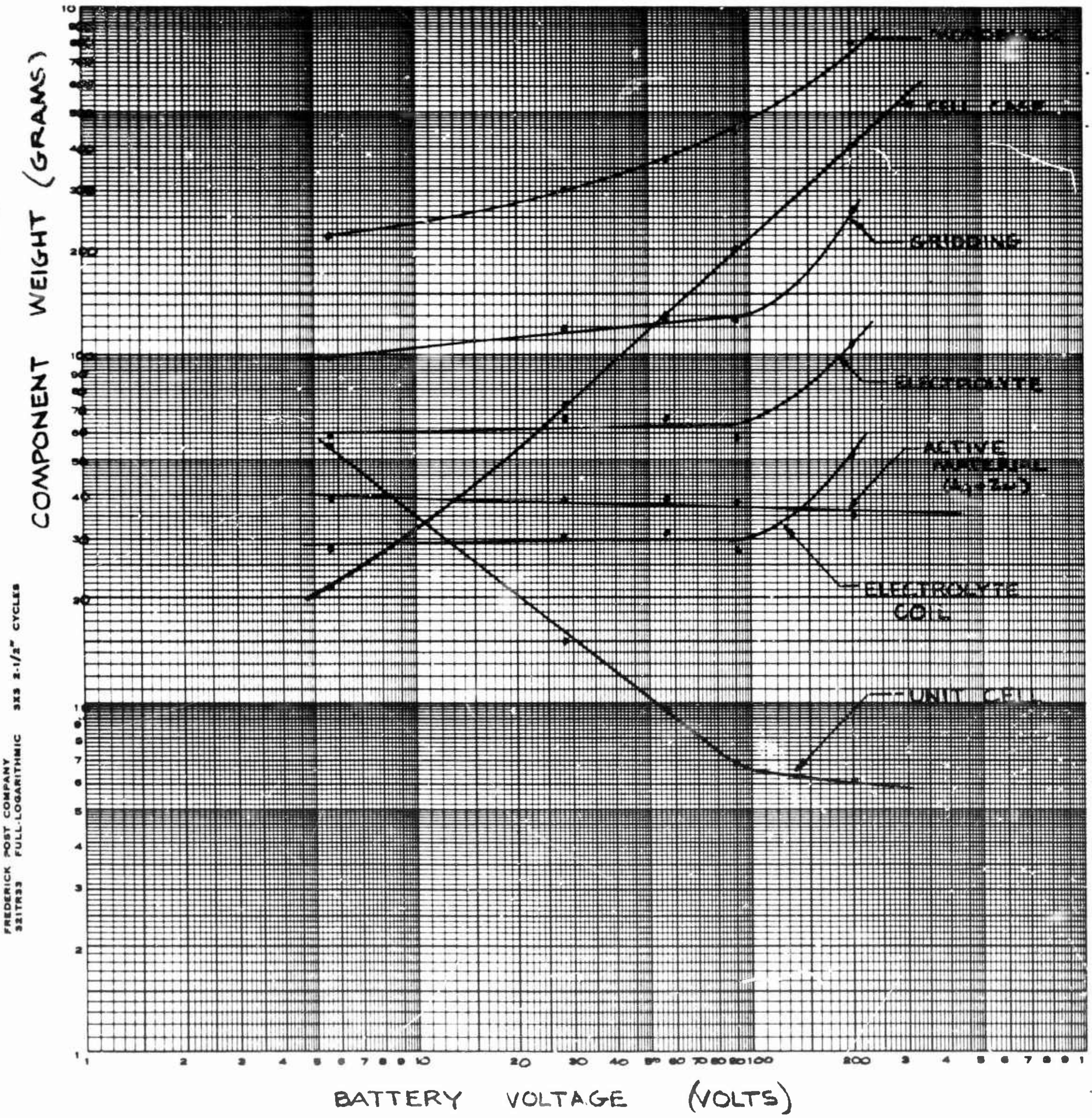
(Battery-Converter System)

2 - 20 KW Battery Output

Summary of Data

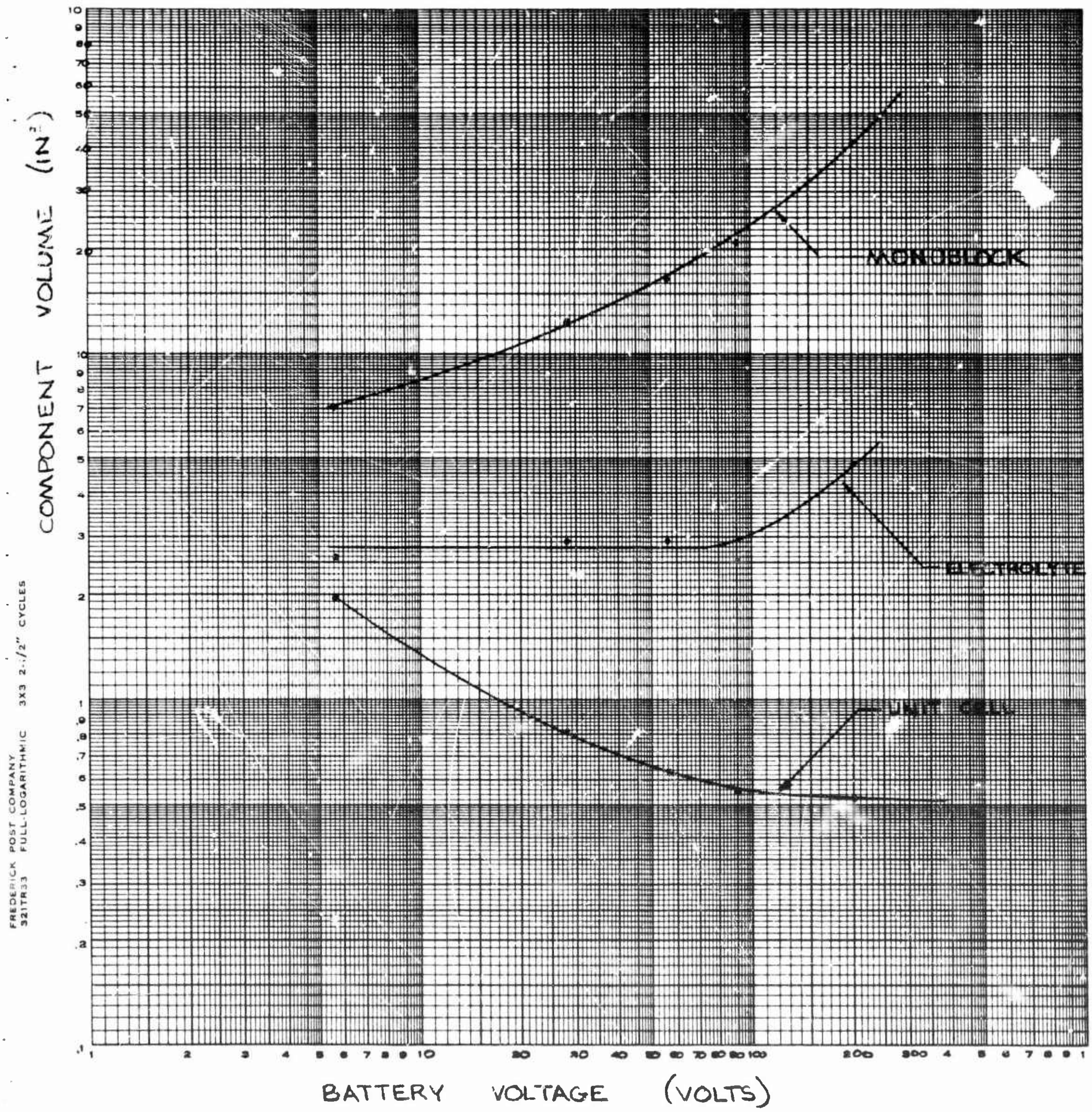
BATTERY OUTPUT: 833 WATT-HOURS AT 2KILOWATTS

VOLTAGE REGULATION: ±10%



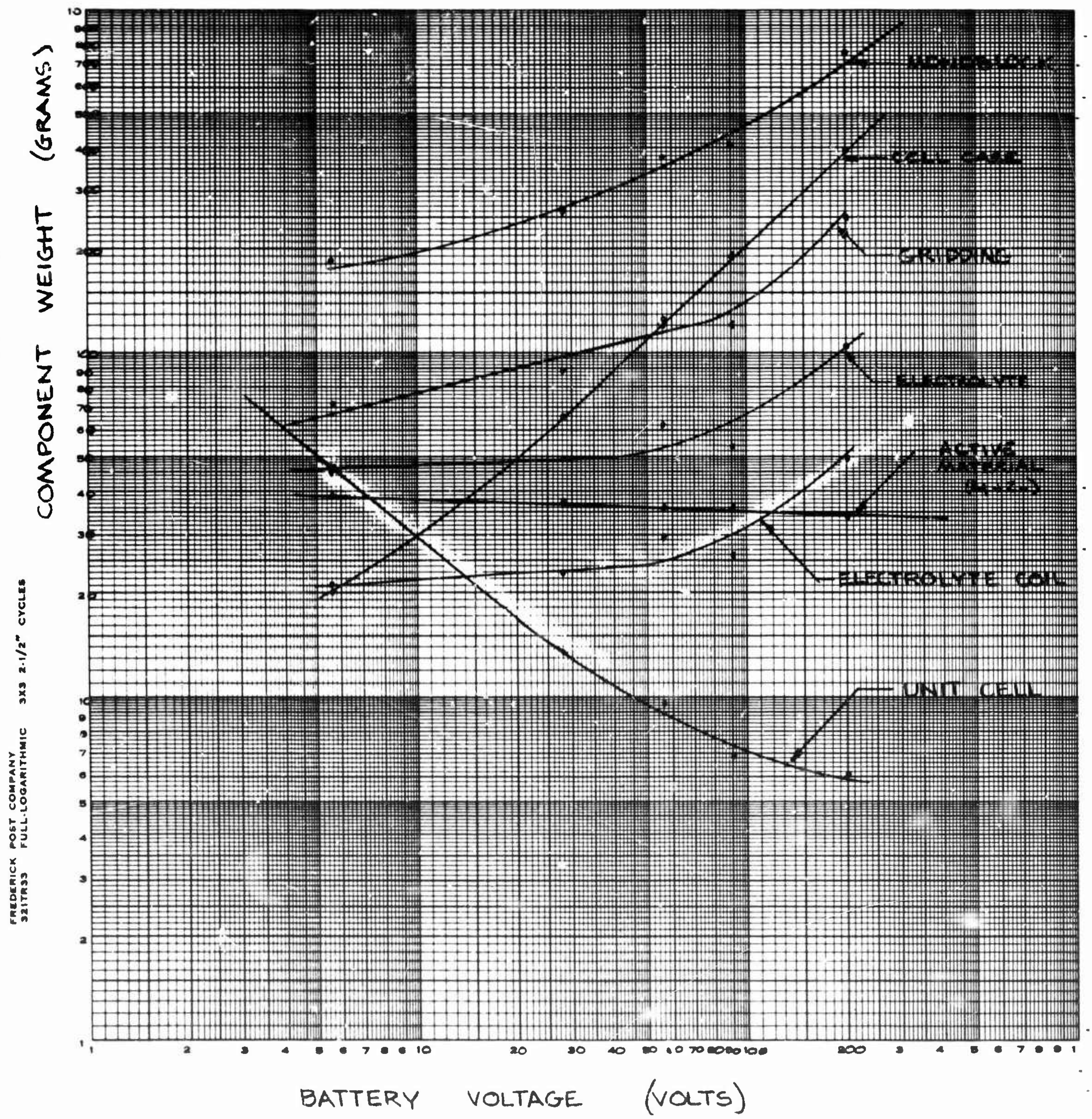
BATTERY OUTPUT: 8.33 WATT-HOURS AT 2 KILOWATTS

VOLTAGE REGULATION: ±10%



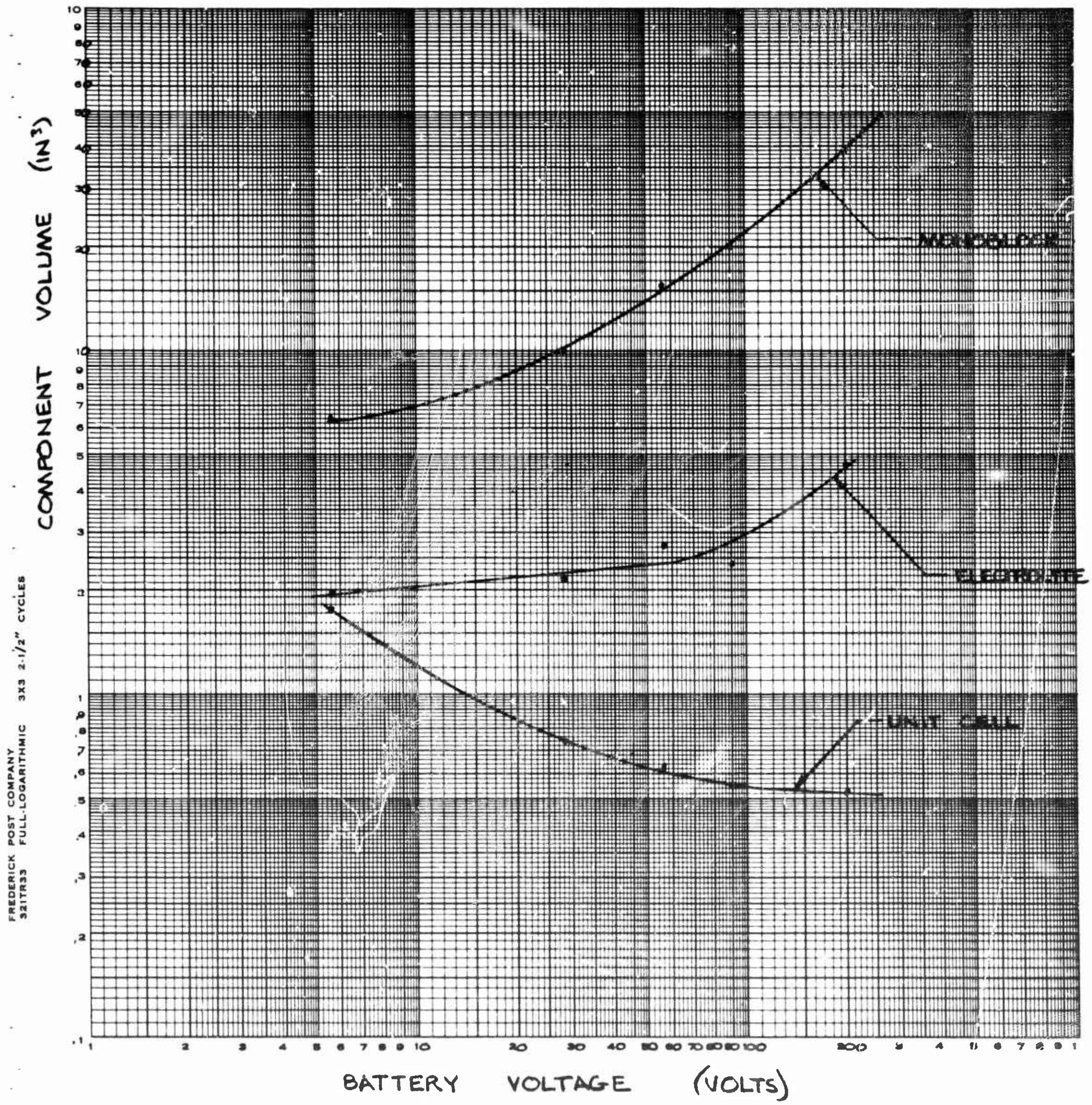
BATTERY OUTPUT : 8.33 WATT-HOURS AT 2 KILOWATTS

VOLTAGE REGULATION: ±15%



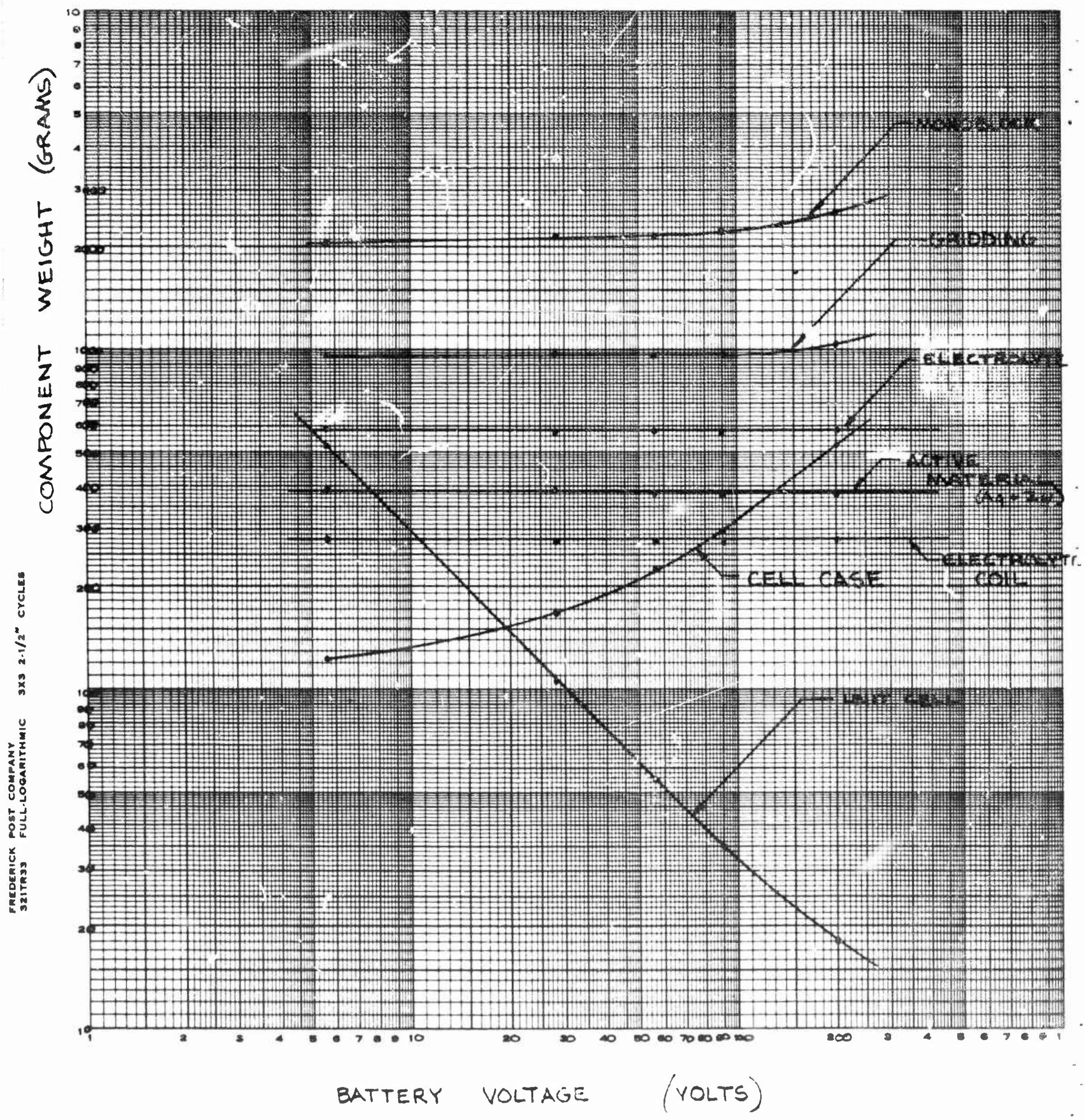
BATTERY OUTPUT: 8.33 WATT-HOURS AT 2 KILOWATTS

VOLTAGE REGULATION: ± 15%



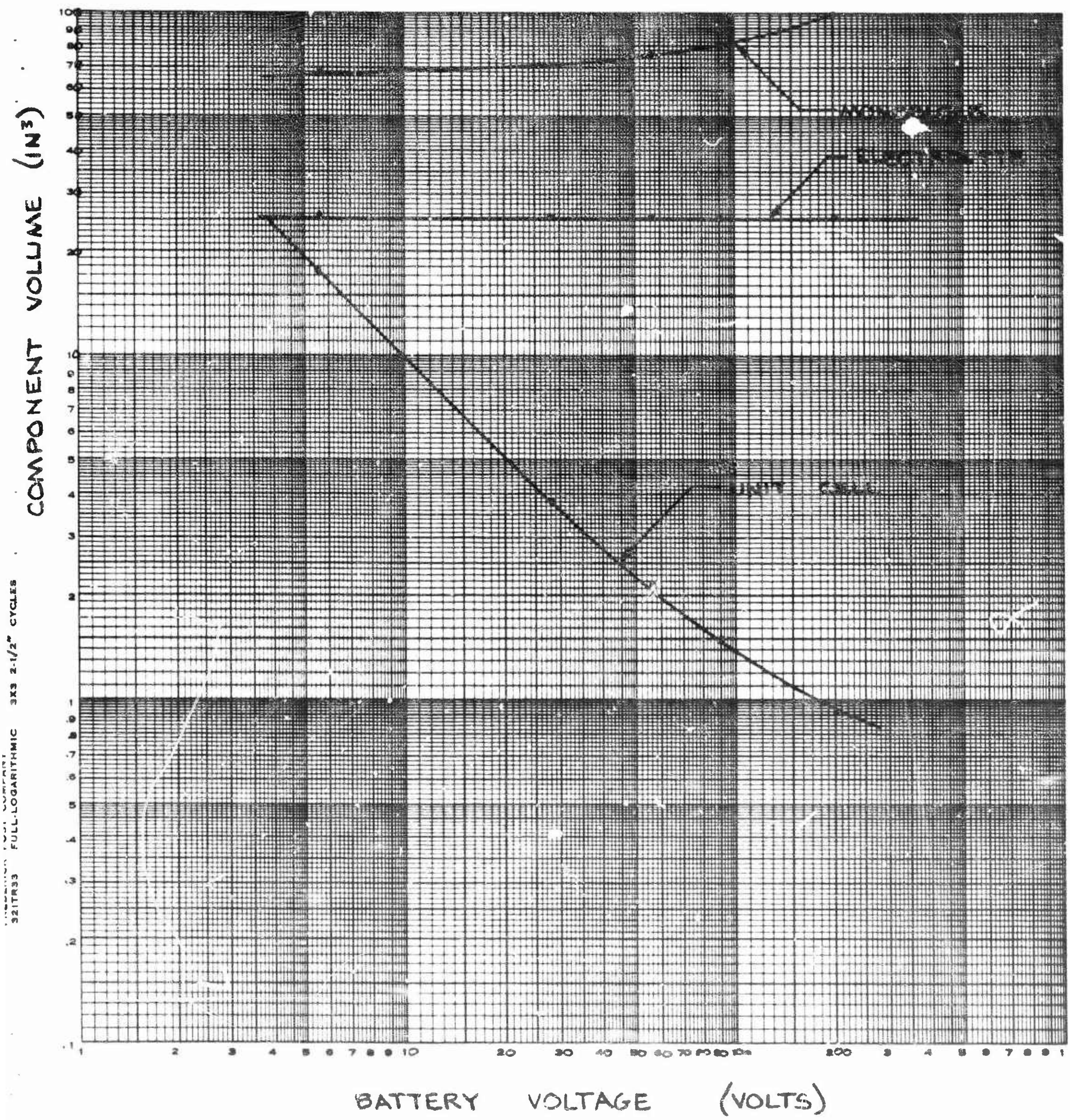
BATTERY OUTPUT: 83.3 WATT-HOURS AT 20 KILOWATTS

VOLTAGE REGULATION: ± 10%



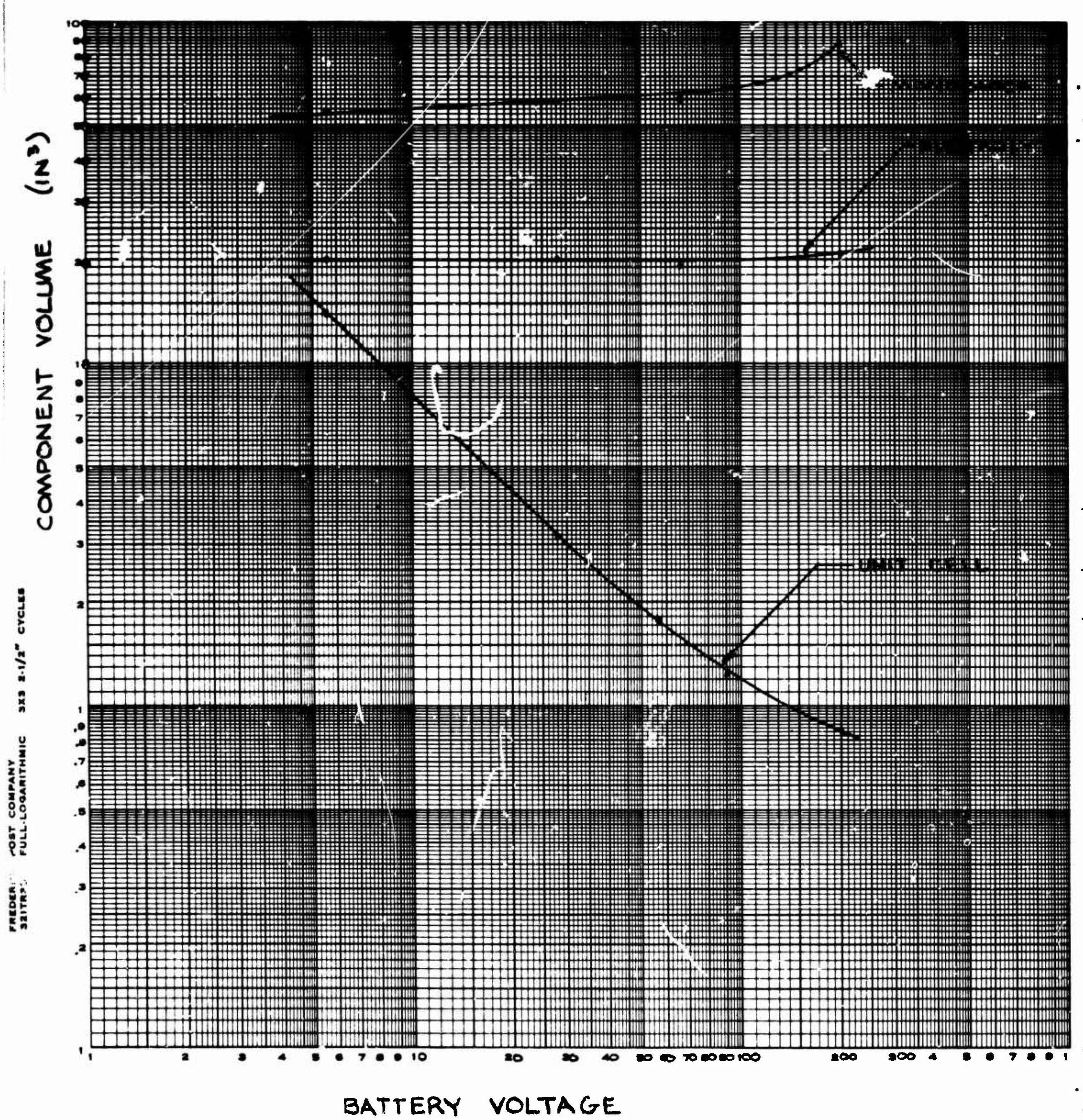
BATTERY OUTPUT: 83.3 WATT-HOURS AT 20 KILOWATTS

VOLTAGE REGULATION: ±10%



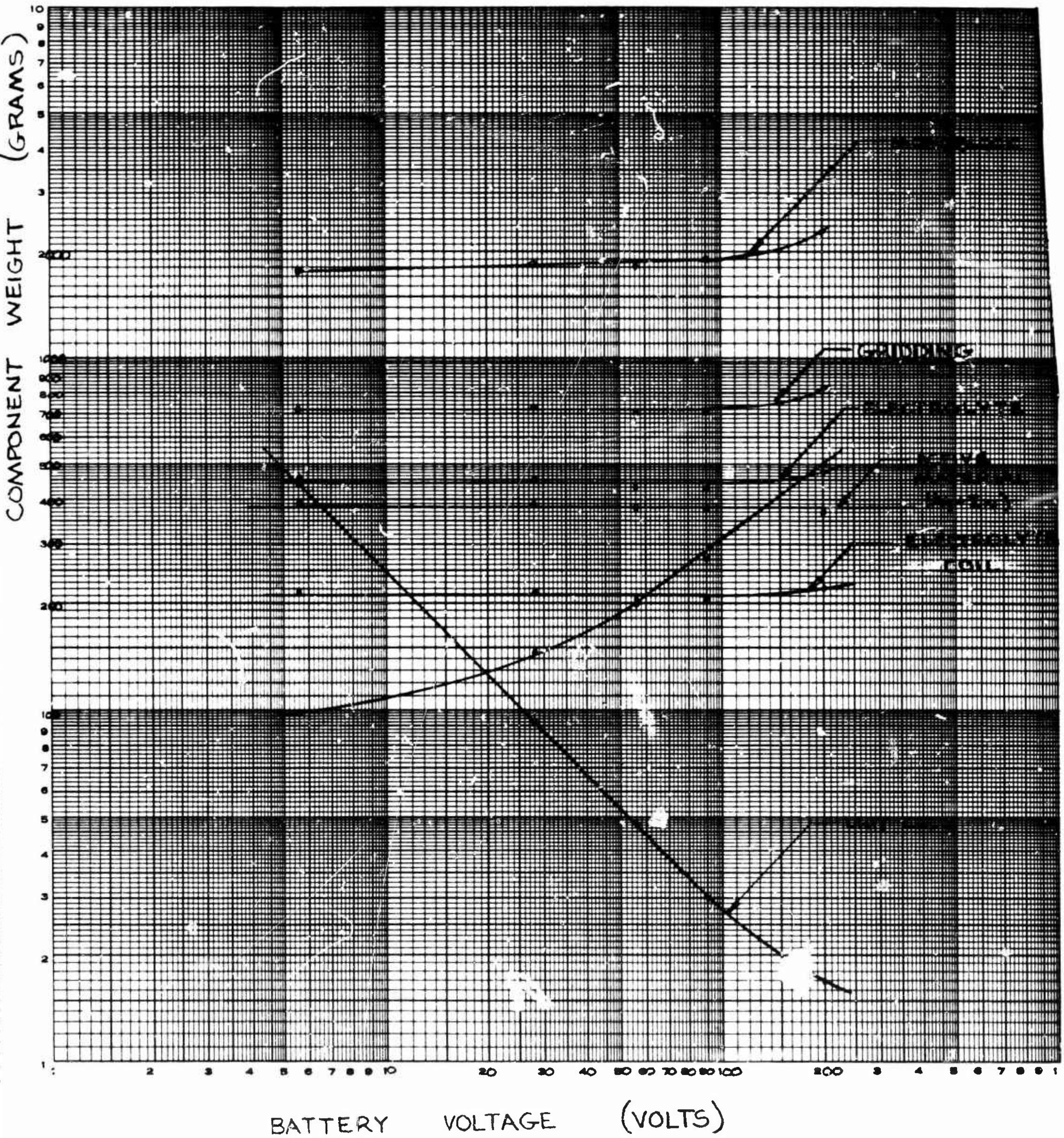
BATTERY OUTPUT: 83.3 WATT-HOURS AT 20 KILOWATTS

VOLTAGE REGULATION: ±15%



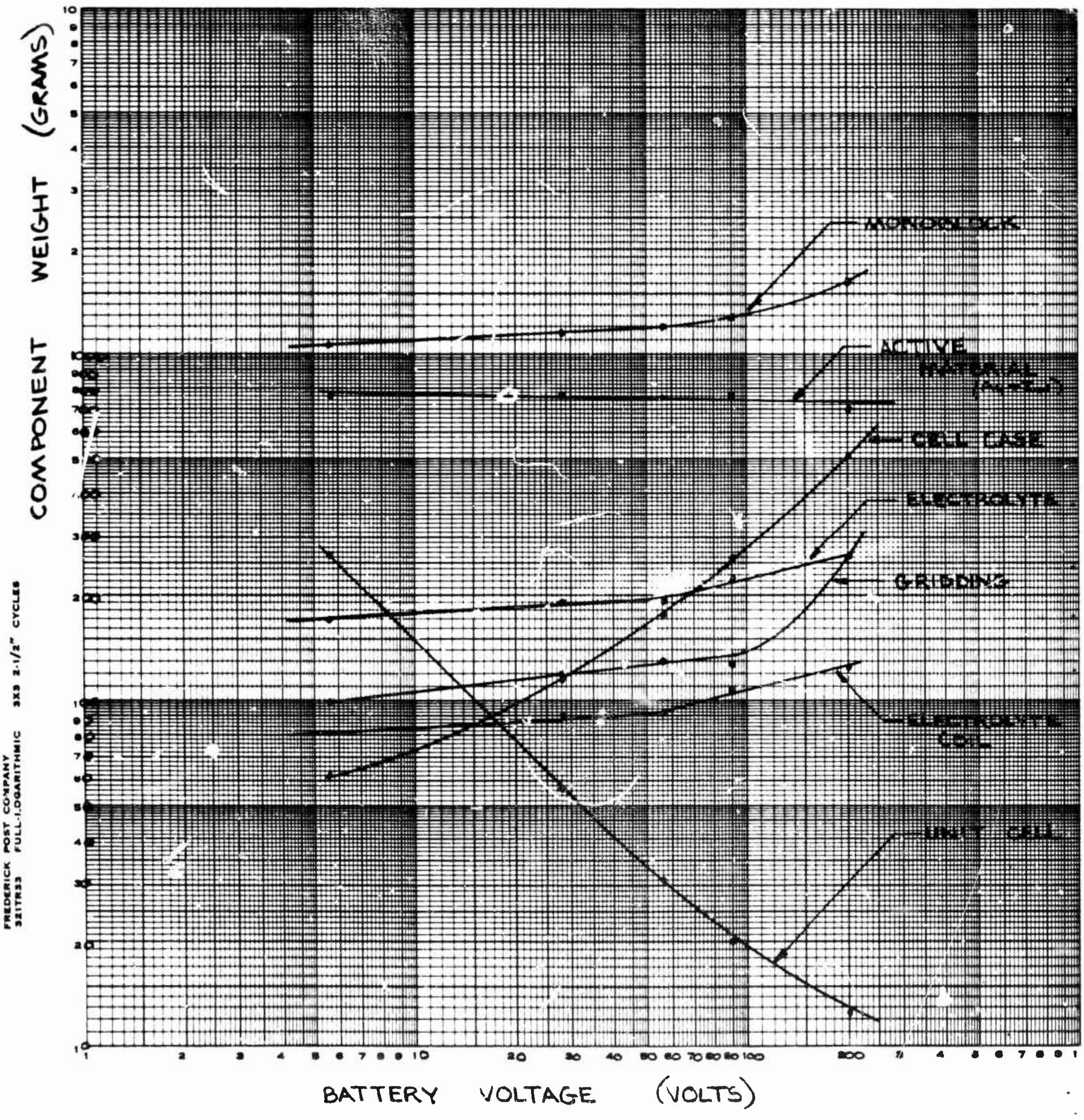
BATTERY OUTPUT : 83.3 WATT-HOURS AT 20 KILOWATTS

VOLTAGE REGULATION : ± 15%

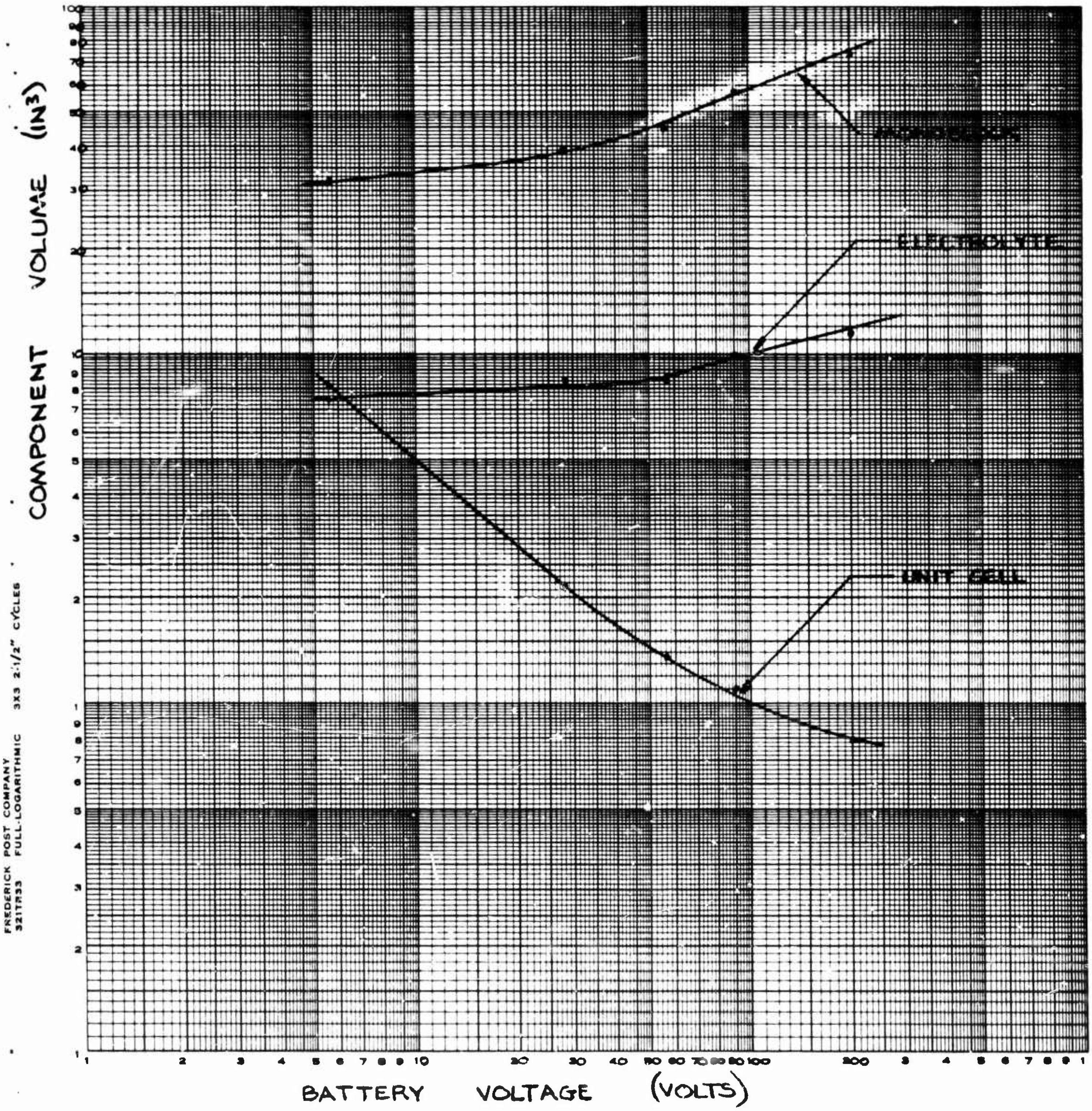


BATTERY OUTPUT. 167 WATT-HOURS AT 2 KILOWATTS

VOLTAGE REGULATION: ±10%

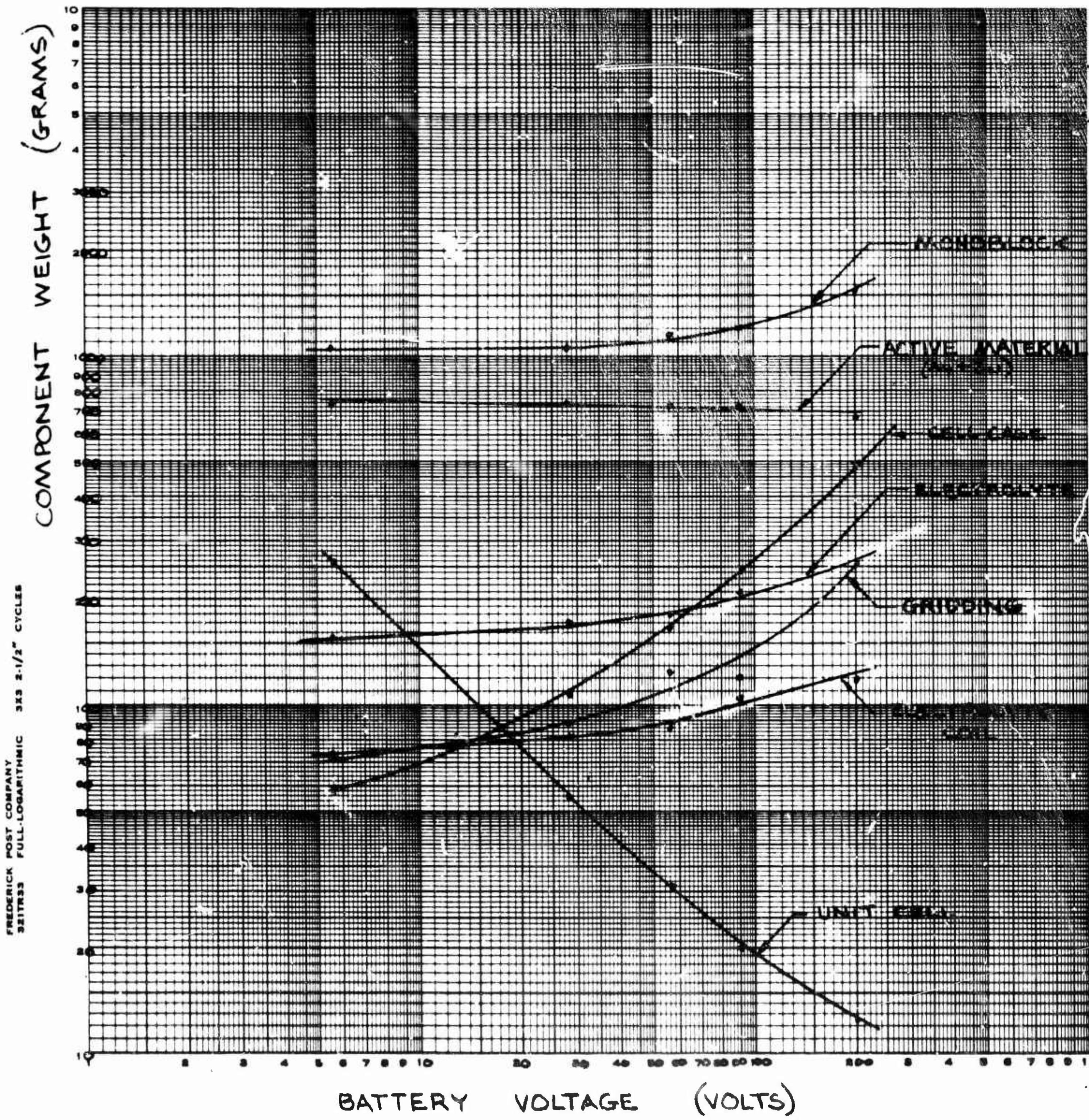


BATTERY OUTPUT 167 WATT-HOURS AT 2KILOWATTS
VOLTAGE REGULATION ±10%



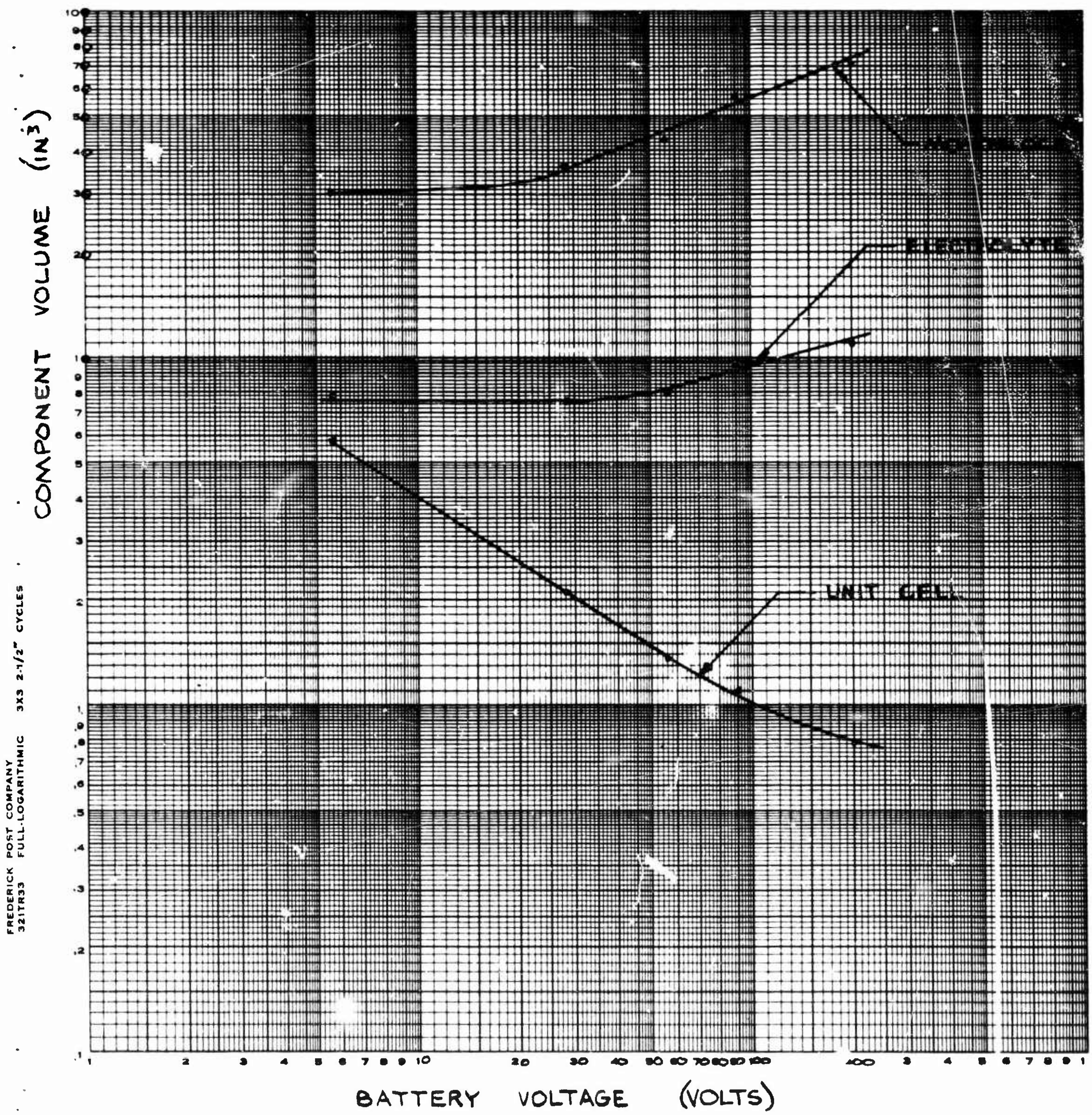
BATTERY OUTPUT 167 WATT-HOURS AT 2 KILOWATTS

VOLTAGE REGULATION ±15%



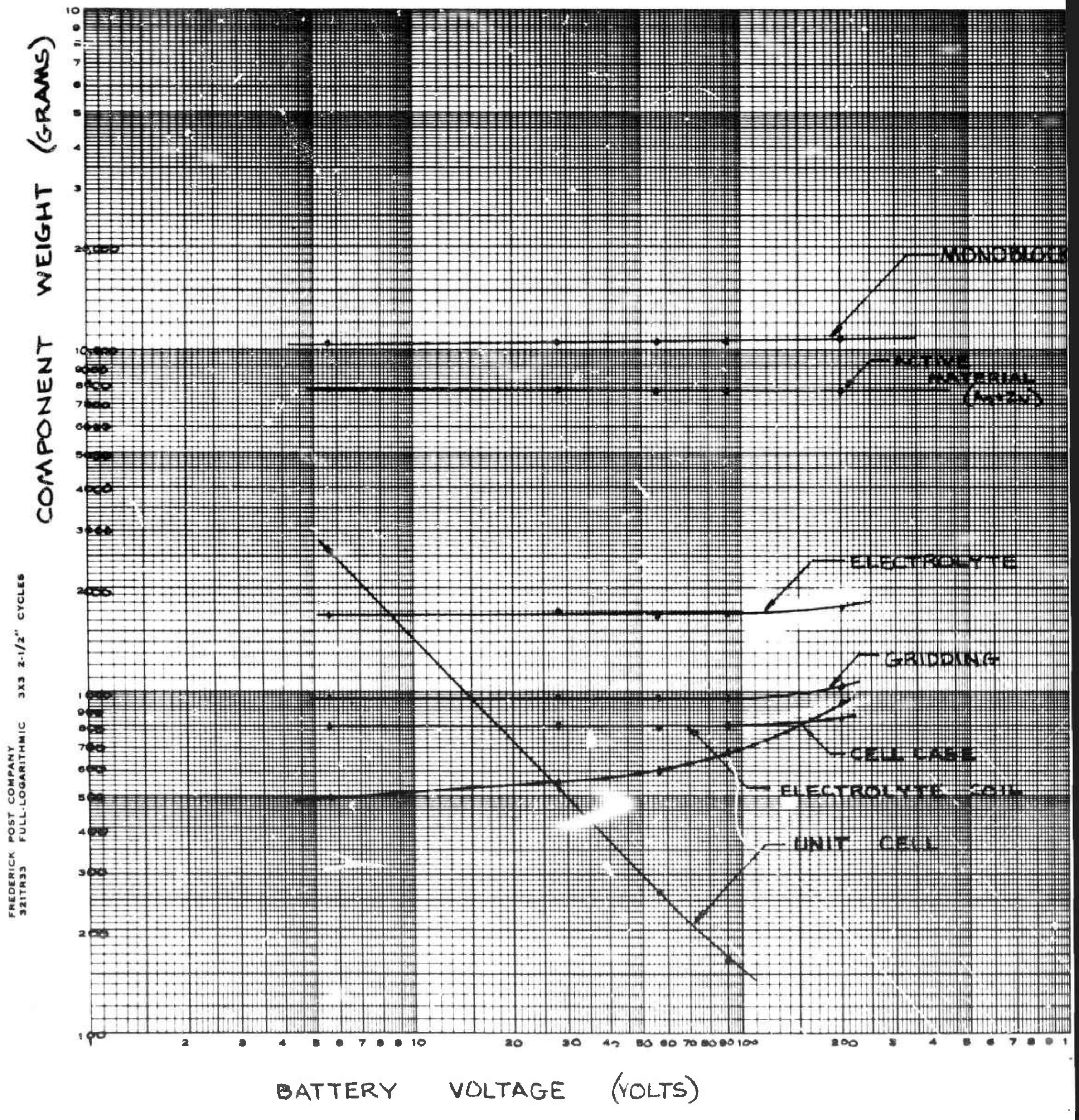
BATTERY OUTPUT: 167 WATT-HOURS AT 2KILOWATTS

VOLTAGE REGULATION: ±15%



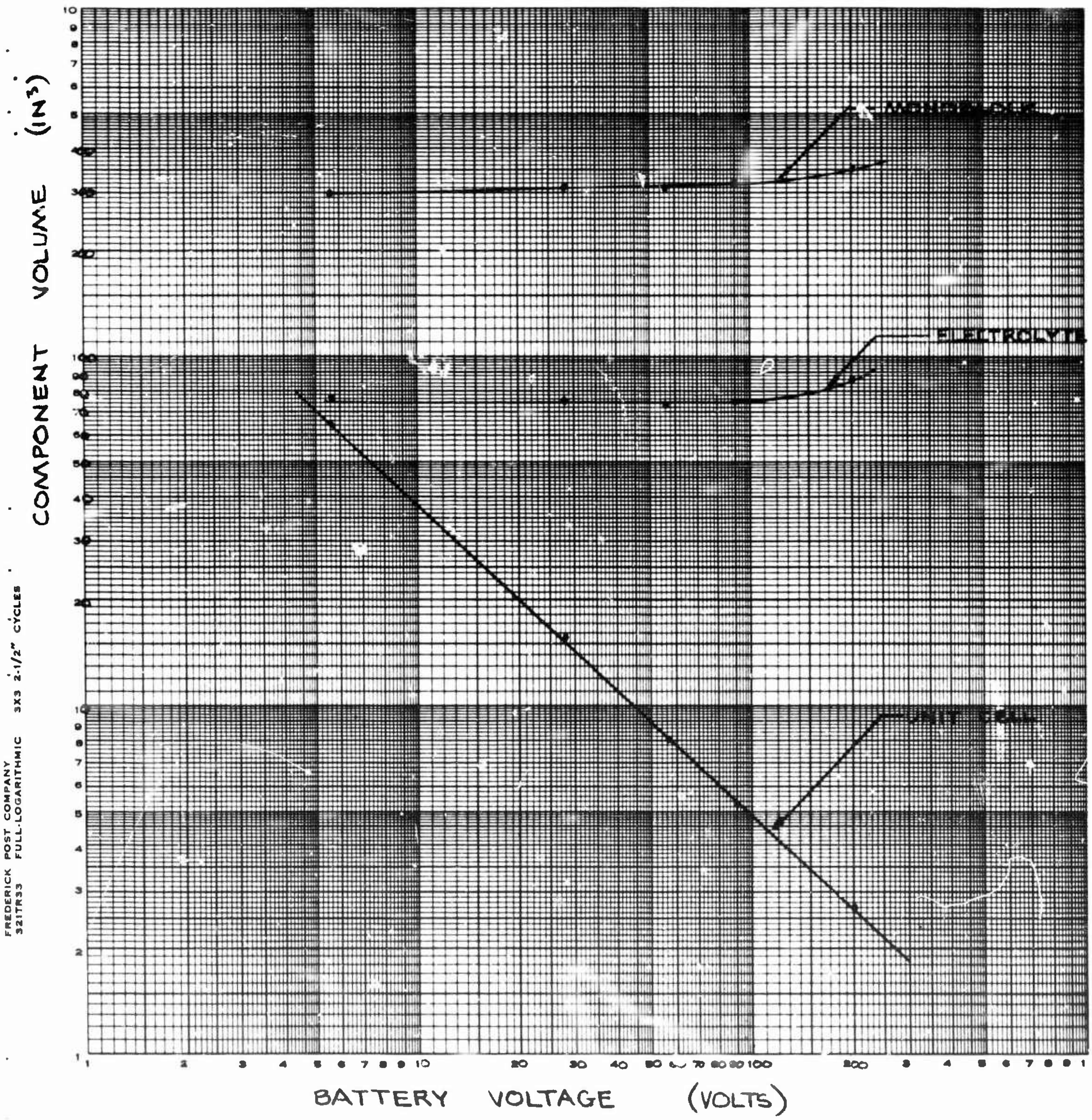
BATTERY OUTPUT: 1670 WATT-HOURS AT 20 KILO WATTS

VOLTAGE REGULATION: ± 10%



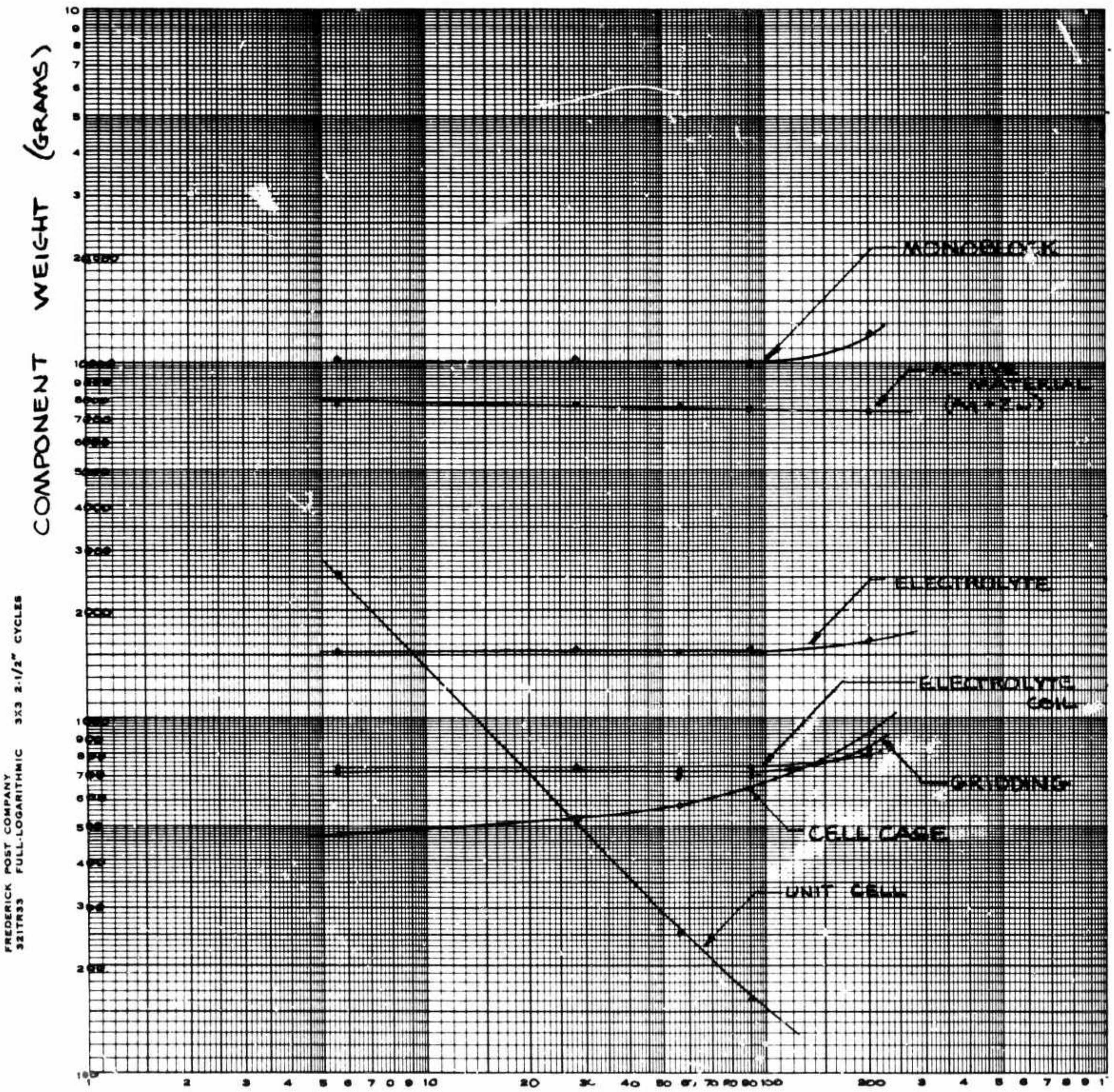
BATTERY OUTPUT: 1670 WATT-HOURS AT 20 KILOWATTS

VOLTAGE REGULATION: ±10%



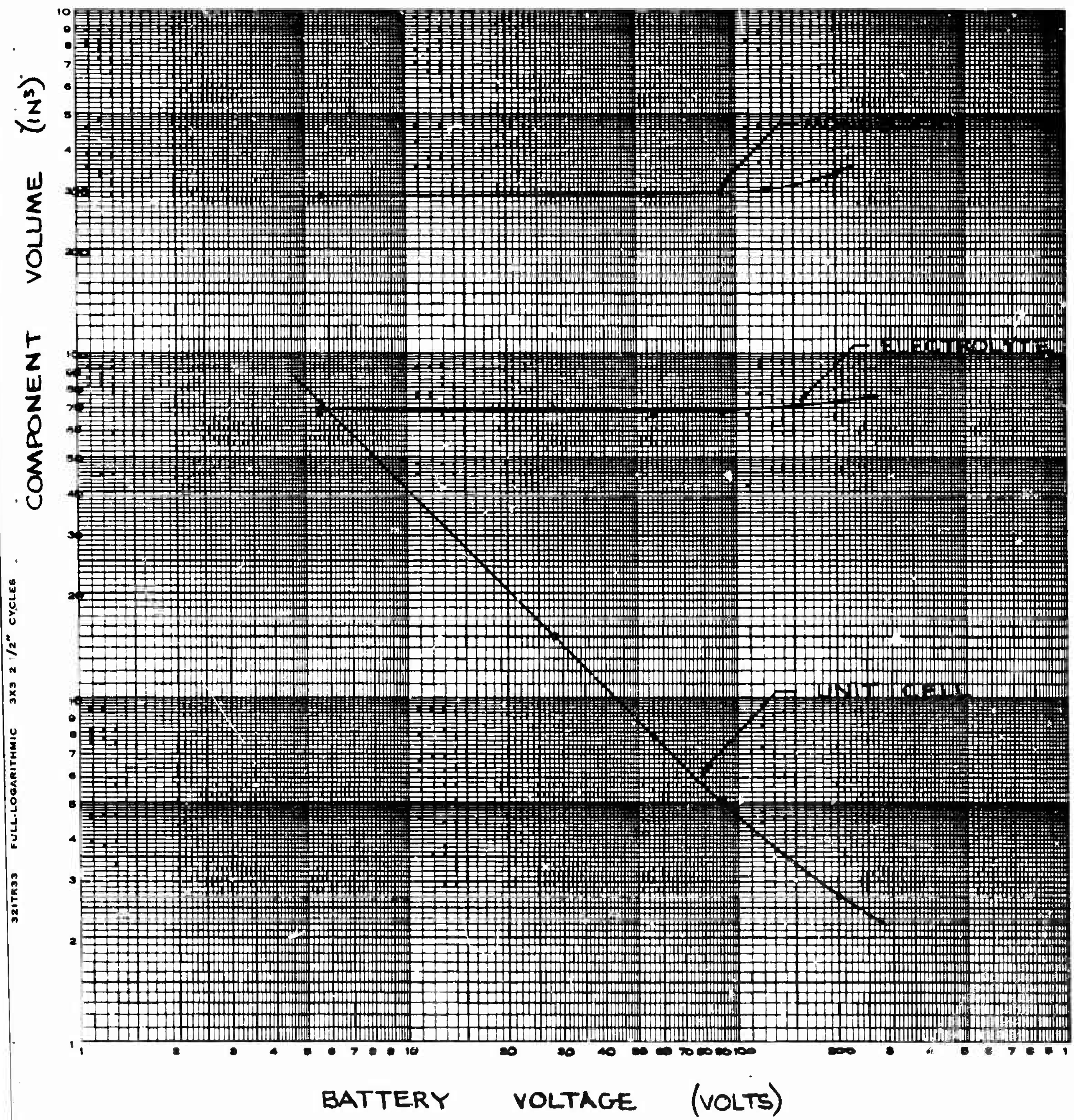
BATTERY OUTPUT: 1670 WATT-HOURS AT 20 KILOWATTS

VOLTAGE REGULATION: ±15%



BATTERY OUTPUT: 1670 WATT-HOURS AT 20 KILOWATTS

VOLTAGE REGULATION: ±15%



APPENDIX II

(Battery-DC/DC Converter Study: Technical Program Plan)

BATTERY-DC/DC CONVERTER STUDY

PROGRAM PLAN

MISSILE POWER SUPPLY CONVERTER

Component Study

1. Survey transistors

Goal - Selection of Transistors with Parameters which are suitable for application.

a) Preliminary Specification Generation

b) Vendor Survey

c) Data Analysis

1) Wt/Vol

2) Switching Speed

3) Losses

4) Trade-offs

5) Reliability-Stress Analysis

...ions

... Survey

Selection of Core materials which merits furth... in...tigation for application

...ary Specifications with Assumptions

... Survey

...ata A...lysis

...) ...orm Factor

2) Losses as Function of Frequency

3) Weight/Volume Data

4) Cross over Points

d) Selection of Materials

3. Battery Analysis

Goal - Definition of Battery characteristics related to system application

a) Preliminary Specification Review

b) Data Analysis

1) Electrical

a) Voltage

b) Activation

c) Impedance

d) Regulation

2) Mechanical

a) Weight

b) Volume

c) Configuration

d) Terminals

3) Thermal

a) Internal

b) External

c) Trade off Studies

4. Transformer Construction Study

a) Weight and Volume

1) High Altitude

2) High Temperature

3) High Voltage

b) Determine Optimum Dimensions

c) Evaluate Construction Techniques

Task II - System Study

1. Analyze Circuit Design Concepts

   a) Battery Voltage vs. Circuit Approach

   b) System Weight/Volume Trade-offs

      1) Efficiency

      2) Thermal

      3) Reliability

2. Conclusions

   a) Battery Size vs. Power

   b) Battery Size vs. Voltage

   c) Converter Size vs. Voltage

   d) Converter Size vs. Input Voltage

   e) Converter Size vs Efficiency

   f) Converter Size vs. Frequency

   g) Converter Size vs. Temperature Limit

   h) Converter Size vs. Power Output

3. General Applications

   a) Component Evaluations

   b) Design Procedures Methodology

   c) Families of Design Curves

BATTERY - DC/DC CONVERTER STUDY

TRADE-OFF AND INVESTIGATION PHASE

TECHNICAL PLAN

1.0 Transistor Survey

(a) Objective: To determine which transistors currently available are most suitable for the application.

(b) Approach: Using preliminary specifications as a basis, select as many transistors as practical which meet the requirements for the missile power supply converter application. Conduct comparative analyses of transistors selected to determine which transistors are most desirable for applications. Order samples. Test samples. Recommend according to test results.

(c) Research Procedures: Conduct "state-of-the-art" survey of several transistor manufacturers. Conduct an analysis of transistor samples; compile data on the following transistor characteristics:

(1) Weight and volume
(2) Losses vs. operating frequency
(3) Reliability versus stress

Conduct trade-off studies between all transistor samples to determine the most desirable transistor(s) for the application.

(d) Test Procedures: The following parameters will be tested for each of the transistor samples:

(1) Vce (sat)
(2) hFE
(3) t on
(4) t off
etc.

(e) Anticipated Performance: Utilizing the information obtained from transistor manufacturers and tests, the design constraints imposed by transistor selection will be determined. The effects of these constraints on system weight and volume will be analyzed during the system study portion of this program.

(f) Milestone: Prepare data describing those transistor types capable of meeting all requirements of the missile power supply converter application. Prepare the data in a form which can be utilized in the system study portion of this program.

2.0 Core Material Study

(a) Objectives: To determine the effects of core material selection on the weight, volume, and efficiency of the converter power transformer and to determine the optimum material available.

(b) Technical Approach: An analysis of core material characteristics to determine the effect of material selection on transformer weight, volume, and efficiency will be performed. The results of this analysis will be presented by curves describing weight, volume and core loss as a function of operating frequency and power handling capability.

(c) Research Procedures: Conduct a "state-of-the-art" survey of core material manufacturers to select the types of core materials which merit further analysis. Test samples of each core material selected to obtain data not readily available from the vendors.

Conduct trade-off studies to determine the most suitable core materials for the missile power supply converter application.

(d) Test Procedures: Each of the core material samples will be tested to obtain data not readily available from the vendors. Test procedures will be written after vendor survey and analysis is completed.

(e) Anticipated Performance: Using the data obtained from the vendors and tests in paragraph (d), the most desirable core material(s) for the missile power supply converter will be established.

(f) Milestone: Prepare data describing those core materials most suitable for the missile power supply converter application in a form which can be used in the system study portion of this program.

3.0 Battery Analysis

(a) Objective: To determine the factors affecting battery weight and volume when analyzed in terms of system requirements, and to reduce these data to a [illegible]m usable in the systems study portion of this program.

(b) Approach: Analyze data supp[illegible]ed by Yardney Electri[illegible] Corp. and reduce to curves of battery weight and v[illegible]lume versus W-H [illegible]ing and regulation requirements.

(c) Rese[illegible]h [illegible]dures: Not appli[illegible]able; research will be performed by Yardney [illegible]ric Corp.

(d) [illegible] Pr[illegible]ocedures: Not [illegible]icable; tests will be performed by Yardney Electric Corp.

(e) Anticipated Performance: Utilizing the results of the analysis, data will be presented in a form which will be usable in the system study portion of this study.

(f) Milestone: Document formulae and prepare graphs of the results of the battery weight and volume study.

4.0 Transformer Construction Study

(a) Objective: To determine the effects of system requirements on transformer construction techniques and how these effects are related to transformer weight and volume, and to present these data in a form usable in the system study portion of this program.

(b) Approach: The effects of high operating voltages, high temperature operation and atmospheric pressures characteristic of re-entry vehicles on the construction techniques required in the transformer will be determined. These data, when combined with the data generated during the core material study, will provide trade off data of transformer weight and volume in a form usable in the systems study portion of this program.

(c) Research Procedure: The design constraints imposed by the operational and environmental conditions on the transformer design will be evaluated in terms of insulation requirements. A suitable winding insulation material and transformer construction technique will be established.

From these data a realistic winding factor will be determined; and, when combined with data generated during the core material study, will provide transformer weight and volume data in a form usable in the system study portion of this program.

(d) Test Procedures: Not applicable to this portion of the study program.

(e) Anticipated Performance: From the data obtained from the studies, an optimum construction method for the transformer will be established, and weight and volume data will be provided for system studies.

(f) Milestone: Prepare document of results of analysis, with recommendations for construction techniques optimized for the application, and provide weight and volume data in a form usable in the system design study portion of the program.

5.0 Analyze Circuit Design Concepts

(a) Objective: To determine an optimized missile power supply converter circuit configuration and battery combination for the application.

(b) Approach: Utilizing the data generated in the components study phase of this program, weight, volume, thermal analysis and reliability studies on specific battery-converter combinations will be performed to establish comparative data for the specific design approaches.

(c) Research Procedures: Conduct weight, volume, thermal analysis, and reliability studies on specific battery-converter combinations and determine the effects of varying battery voltage, operating frequency and converter efficiency on the overall system design.

(d) Test Procedures: Not applicable to this portion of the study program.

(e) Anticipated Performance: From the data obtained in this systems study, a recommended circuit will be established for development in phase II of this program. In addition, a design procedures methodology and families of design curves applicable to systems of different requirements will be established.

(f) Milestone: Establishment of a recommended circuit for development during phase II of this program and a design procedure methodology including curves or formulae describing the following:

(1) Battery weight versus W-H rating and regulation
(2) Battery volume versus W-H rating and regulation
(3) Battery weight versus terminal voltage and regulation
(4) Battery volume versus terminal voltage and regulation
(5) Converter volume versus battery voltage
(6) Converter weight versus battery voltage
(7) Converter volume versus operating frequency
(8) Converter weight versus operating frequency
(9) Converter volume versus power output
(10) Converter weight versus power output
(11) Converter volume versus output voltage
(12) Converter weight versus output voltage
(13) Converter operating temperature versus converter size and operating time.

APPENDIX III

(Honeywell Inc. - Quarterly Technical Progress Report)

QUARTERLY TECHNICAL PROGRESS REPORT

TO

YARDNEY ELECTRIC CORPORATION

Period Covering April 20, 1966 to July 25, 1956

Contract No. P.O. 57636

Prepared by

R. L. Carlson
Project Engineer

Approved by

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Project Supervisor

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Section Head
Electronics and
Power Conditioning

Honeywell Inc.
Military Products Group
ORDNANCE DIVISION
Hopkins, Minnesota

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS

LIST OF TABLES

SECTION I

INTRODUCTION

This report describes the results of studies performed by Honeywell Ordnance from April 20, 1966 to July 25, 1966, to develop a design methodology for a missile power supply. Batteries and converter-regulator and battery combinations were investigated and evaluated.

This program has the following major objectives:

- Development of a design methodology for a highly reliable missile power supply for operation from a silver-zinc battery source.

- Development of a reliable method for accurately determining the minimum weight and volume of the missile power supply.

To meet these objectives, the applicability of the following systems and techniques have been studied and evaluated.

- All loads serviced by a battery directly

- All loads serviced by a solid-state dc/dc converter operated from a battery source

- A portion of the load serviced by a battery or batteries directly, with the remainder of the load serviced by a solid-state dc/dc converter.

In general, the missile power supply is characterized by a relatively high power output during a relatively short, one-time operation. Accordingly, this program includes studies of the effects of relatively high frequency

operation, boil-off cooling, high quality cores, and the effects of overloads in a power supply of this type.

The design methodology is sufficiently generalized to be applicable to other similar systems of various power levels, voltage levels, and load transfer durations.

SECTION II

TECHNICAL DISCUSSION

1. BATTERY WEIGHT AND VOLUME ANALYSIS

During the report period, data were obtained describing the weight and volume of batteries with conventional (individual) cell construction. Formulae were derived expressing the weight and volume of the batteries as a function of nominal battery terminal voltage, watt-hour rating, and percent of regulation.

The formulae for battery volume are:

$$\text{Vol} = 0.28\,\frac{\text{inches}^3}{\text{volt}} \times V + 0.72\,\frac{\text{inches}^3}{\text{watt-hour}} \times R \text{ at } \pm 5\% \text{ regulation}$$

$$\text{Vol} = 0.28\,\frac{\text{inches}^3}{\text{volt}} \times V + 0.62\,\frac{\text{inches}^3}{\text{watt-hour}} \times R \text{ at } \pm 10\% \text{ regulation}$$

$$\text{Vol} = 0.28\,\frac{\text{inches}^3}{\text{volt}} \times V + 0.53\,\frac{\text{inches}^3}{\text{watt-hour}} \times R \text{ at } \pm 15\% \text{ regulation.}$$

Where:
- Vol = Volume of battery in cubic inches
- V = Nominal battery terminal voltage in volts
- R = Battery energy in watt-hours

The formulae for battery weight are:

$$\text{Weight} = 0.006\,\frac{\text{pounds}}{\text{volt}} \times V + 0.042\,\frac{\text{pounds}}{\text{watt-hour}} \times R \text{ at } \pm 5\% \text{ regulation}$$

$$\text{Weight} = 0.006\,\frac{\text{pounds}}{\text{volt}} \times V + 0.0345\,\frac{\text{pounds}}{\text{watt-hour}} \times R \text{ at } \pm 10\% \text{ regulation}$$

$$\text{Weight} = 0.006\,\frac{\text{pounds}}{\text{volt}} \times V + 0.0295\,\frac{\text{pounds}}{\text{watt-hour}} \times R \text{ at } \pm 15\% \text{ regulation}$$

Where:	Weight	=	Weight of battery in pounds
	V	=	Nominal battery terminal voltage in volts
	R	=	Battery energy in watt-hours

2. CORE MATERIAL SURVEY AND TRANSFORMER ANALYSIS

Letters of inquiry were sent to six core material manufacturers requesting data and recommendations appropriate to this program A copy of this letter appears in Appendix D.

Arnold Engineering did not recommend any of their currently available core materials, but stated that production of soft ferrite cores which may be suitable has just begun. These cores will not be available until late fall 1966; engineering data are not available at the present time.

Indiana General recommended their 0-5 ferrite for the power transformer and C-2 ferrite for switching applications. Data sheets for these materials were supplied.

Allen Bradley recommended their R-03 ferrite core material, and submitted data on this material.

Magnetics, Inc. recommended 1/2-mil Orthonol for use at 20 kc, and supplied data on this material.

Ferroxcube did not reply.

The data received from all manufacturers were deficient in core loss information at high frequency and high temperatures; however, this information is more complete for the ferrites than for the tape-wound cores.

A design methodology was developed for comparing core materials and determining how the system volume is affected by adding a transformer to the system.

Formulae were derived expressing the increase in system volume resulting from the addition of a transformer core and the increase in system volume resulting from the addition of a transformer winding. The derivation of these formulae are presented in Appendix B. Using these formulae, a Honeywell HRC-400 computer was used to generate the data that was then used to develop the curves presented in Figures 1 through 25.

The formula expressing the change in system volume resulting from the addition of the transformer core is:

$$\Delta V_1 = 4.55 \times 10^{-9} \, B t f \, C_{L1} \left(\frac{2.94 \times 10^8 \, P}{f \beta S J K} \right)^{3/4} + \left(\frac{2.94 \times 10^8 \, P}{f \beta S J K} \right)^{3/4}$$

where:

ΔV_1 = Increase in system volume (in cubic inches) due to the addition of the transformer core

B = Battery volume constant, $\frac{\text{inches}^3}{\text{watt-hour}}$

t = Load duration in seconds

f = Frequency of operation in cps

C_{L1} = Core loss in $\frac{\mu \text{ watts}}{\text{cm}^3 \text{ cps}}$

β = Flux density in $\frac{\text{lines}}{\text{inches}^2}$

S = Core stacking factor

P = Power input to the transformer in watts

J = Current density in the conductors of the transformer winding, in $\frac{\text{amperes}}{\text{inches}^2}$

K = A winding factor expressing the ratio of conductor area to window area.

The first term on the right side of the equation, 4.55×10^{-9} Btf C_{L1} $\left(\frac{2.94 \times 10^8 P}{f \beta S K J}\right)^{3/4}$, defines the battery volume increase required to supply the losses of the core, while the second term, $\left(\frac{2.94 \times 10^8 P}{f \beta S K J}\right)^{3/4}$, defines the volume of the core.

Since the power input to the transformer, P, the current density, J, and the winding factor, K, are determined largely by factors other than the transformer core material, these terms were transposed to the left side of the equation, as follows:

$$\left(\frac{KJ}{P}\right)^{3/4} \Delta V_1 = 4.55 \times 10^{-9} \text{ Bt } C_{L1} \left(\frac{2.94 \times 10^8}{f \beta S}\right)^{3/4} + \left(\frac{2.94 \times 10^8}{f \beta S}\right)^{3/4}$$

The factor 4.55×10^{-9} CL_1 $\left(\frac{2.94 \times 10^8}{f \beta S}\right)^{3/4}$, with dimensions of $\frac{\text{watt-hours}}{\text{seconds}}$, is proportional to the power dissipated in the core. This factor is plotted for the Allen Bradley R-03 ferrite core material in Figure 1, and for 2-mil Orthonol in Figure 2.

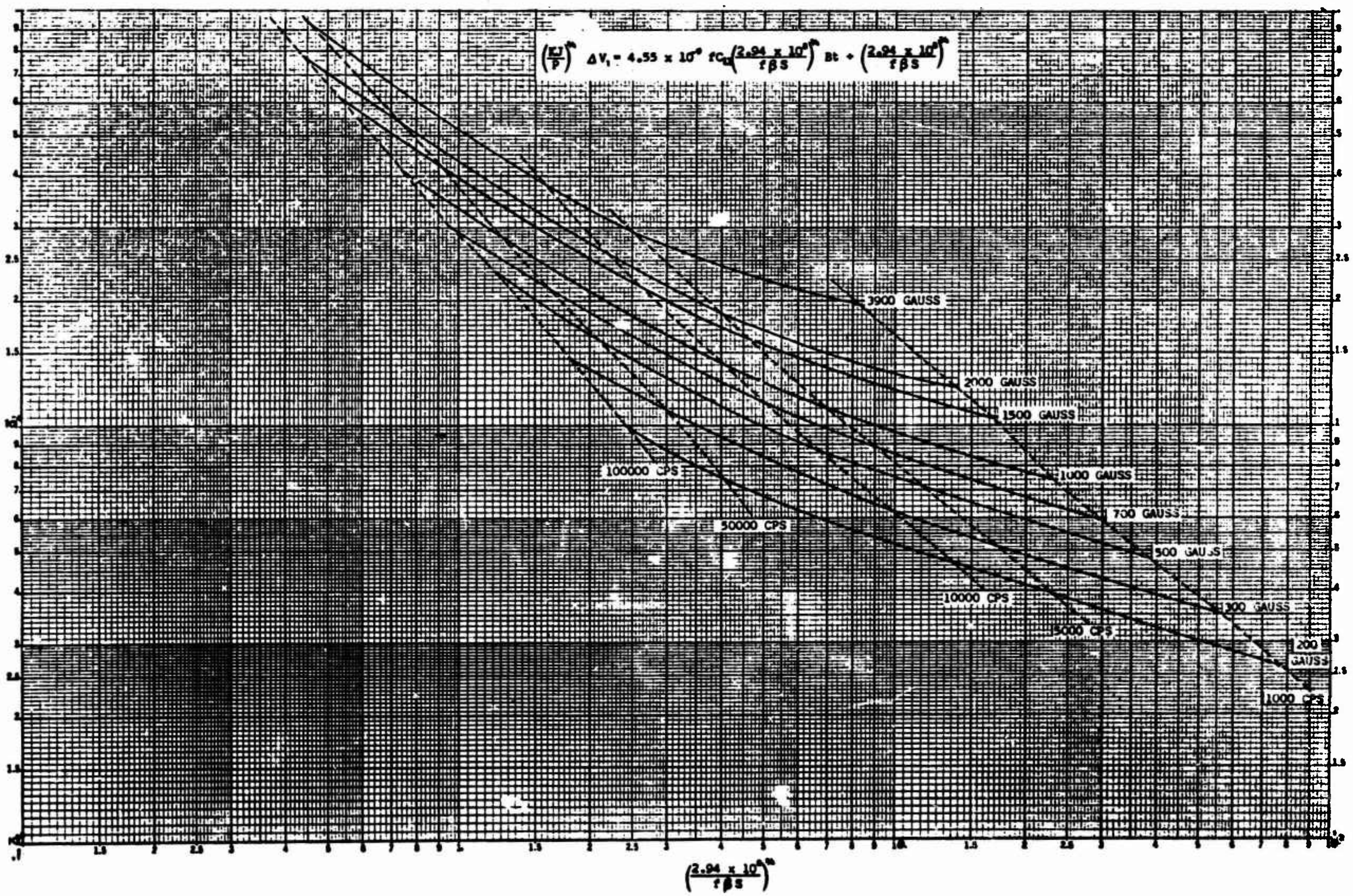


Figure 1 - RO3 FERRITE POWER DISSIPATION VERSUS CORE VOLUME

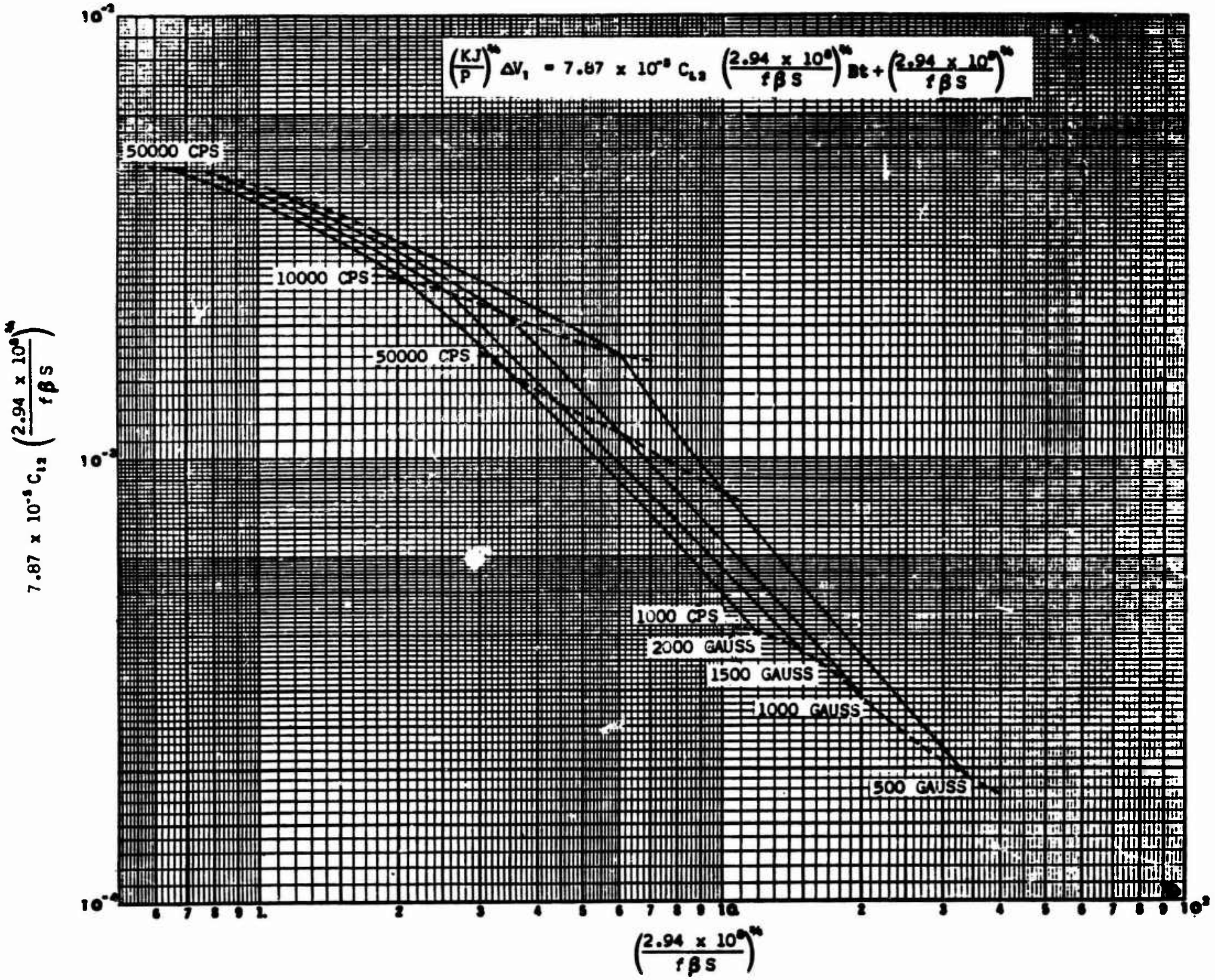


Figure 2 - 2 MIL ORTHONOL POWER DISSIPATION VERSUS CORE VOLUME

Multiplying this factor by specific values for B and t, as determined by the battery constant and load duration, translates this family of curves in the vertical direction.

If the term $\left(\frac{2.94 \times 10^8}{f\,BS}\right)^{3/4}$ is then added, the family of curves becomes asymptotic to a line described by the formula:

$$\left(\frac{KJ}{P}\right)^{3/4} \Delta V_1 = \left(\frac{2.94 \times 10^8}{f\,BS}\right)^{3/4}$$

Where:

ΔV_1 = volume added by core, in cubic inches.

With B equal to 0.53 and 0.62 for battery regulations of 15% and 10%, respectively, and t equal to 45 seconds or 75 seconds (from the specific load durations defined for the system), a series of curves were plotted for R-03 ferrite, 0-5 ferrite, 2-mil Orthonol, and 1-mil Orthonol. These curves are presented in Figures 3 through 18.

NOTE

Three different constants, $4.55 \times 10^{-9}\, fC_{L1}$, $4.55 \times 10^{-6}\, Bt\, C_{L3}$, and $7.87 \times 10^{-3}\, C_{L2}$, appear in the formula presented in Figures 1 through 18. Thus, the formula is expressed in three different ways, with the change in constants resulting from the manner in which the factors describing core loss were inserted into the formula.

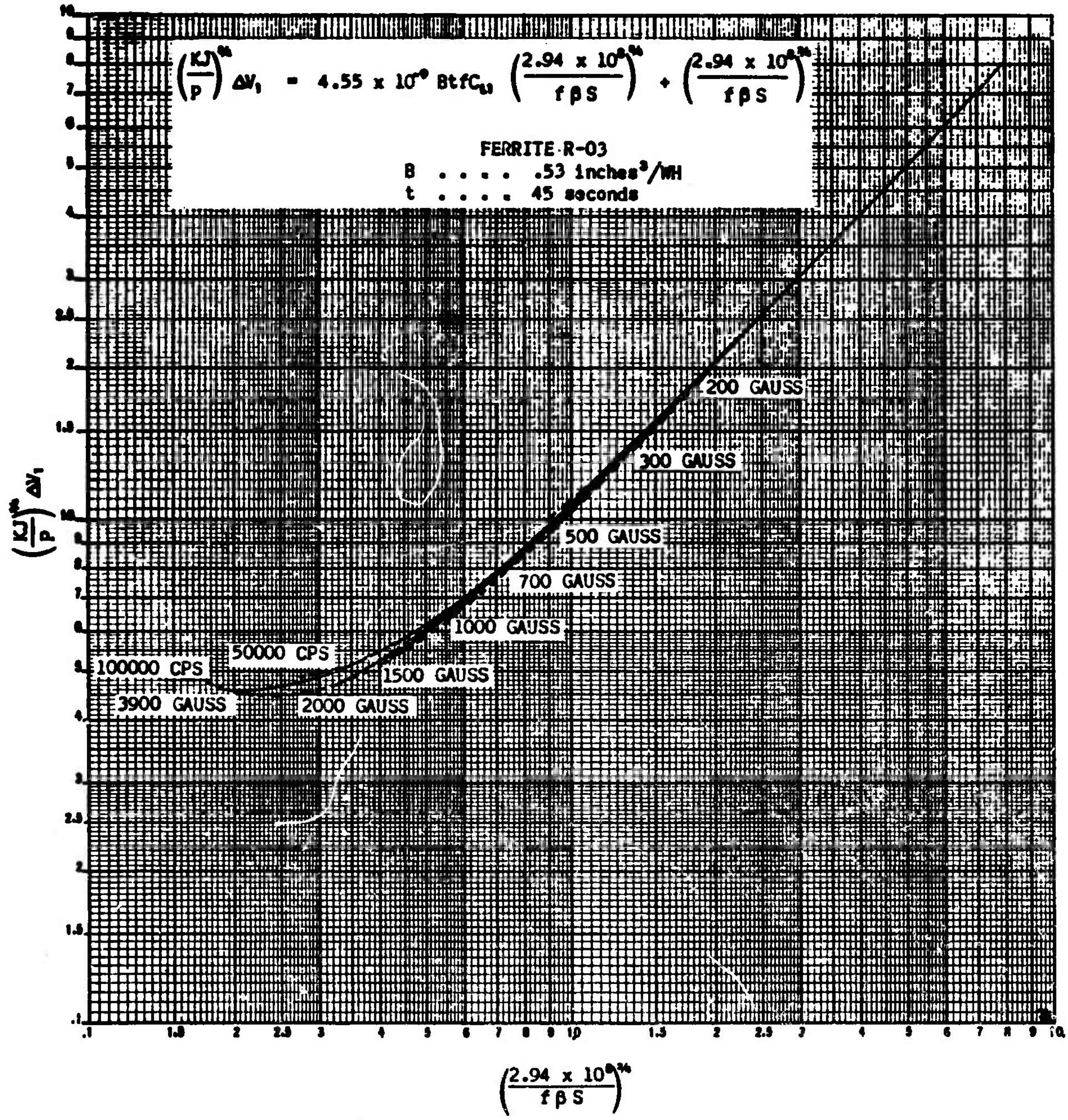


Figure 3 - EFFECT OF R-03 FERRITE ON SYSTEM VOLUME (B = .53 AND t = 45)

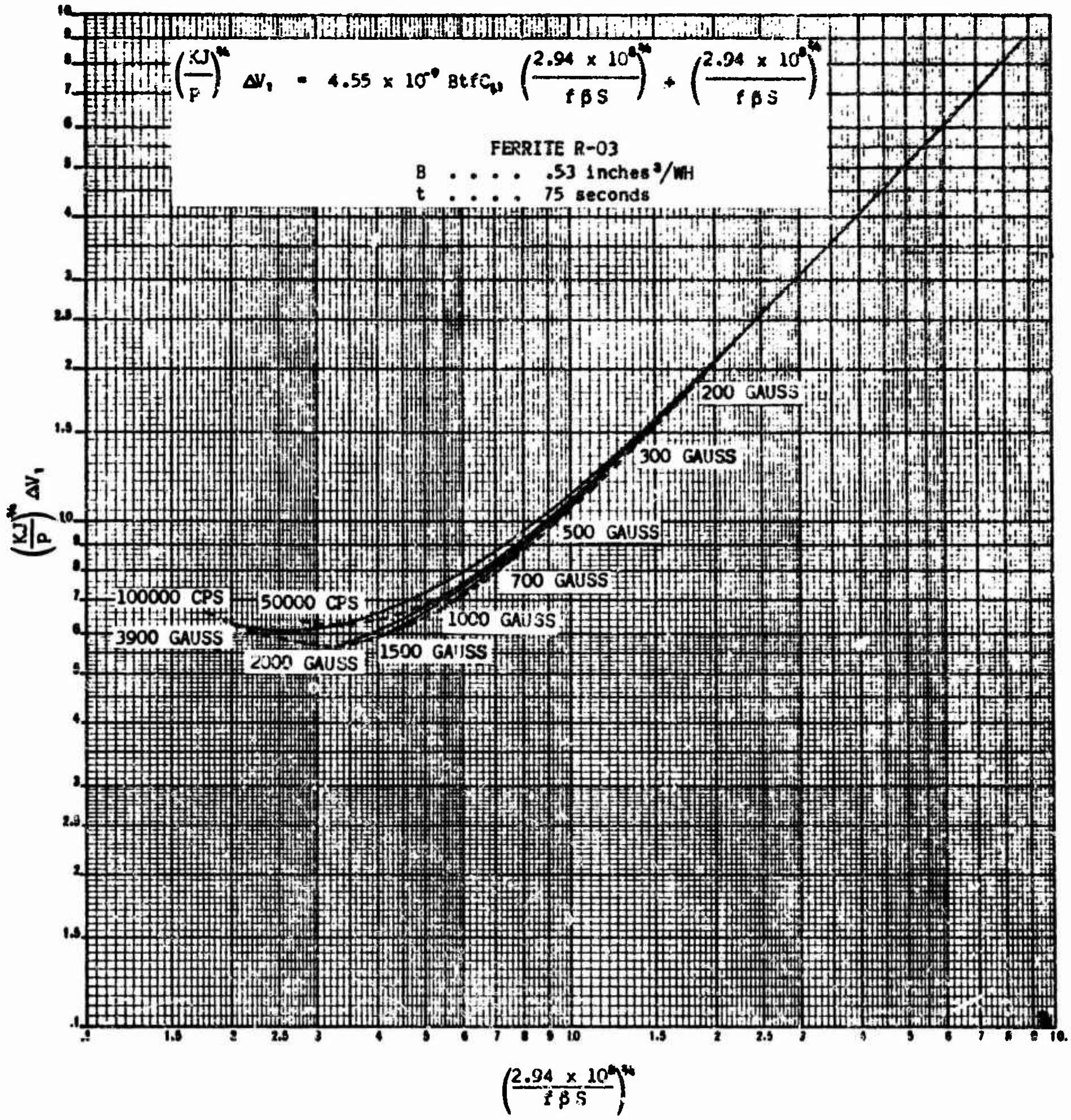


Figure 4 - EFFECT OF R-03 FERRITE ON SYSTEM VOLUME (B = .53 AND t = 75)

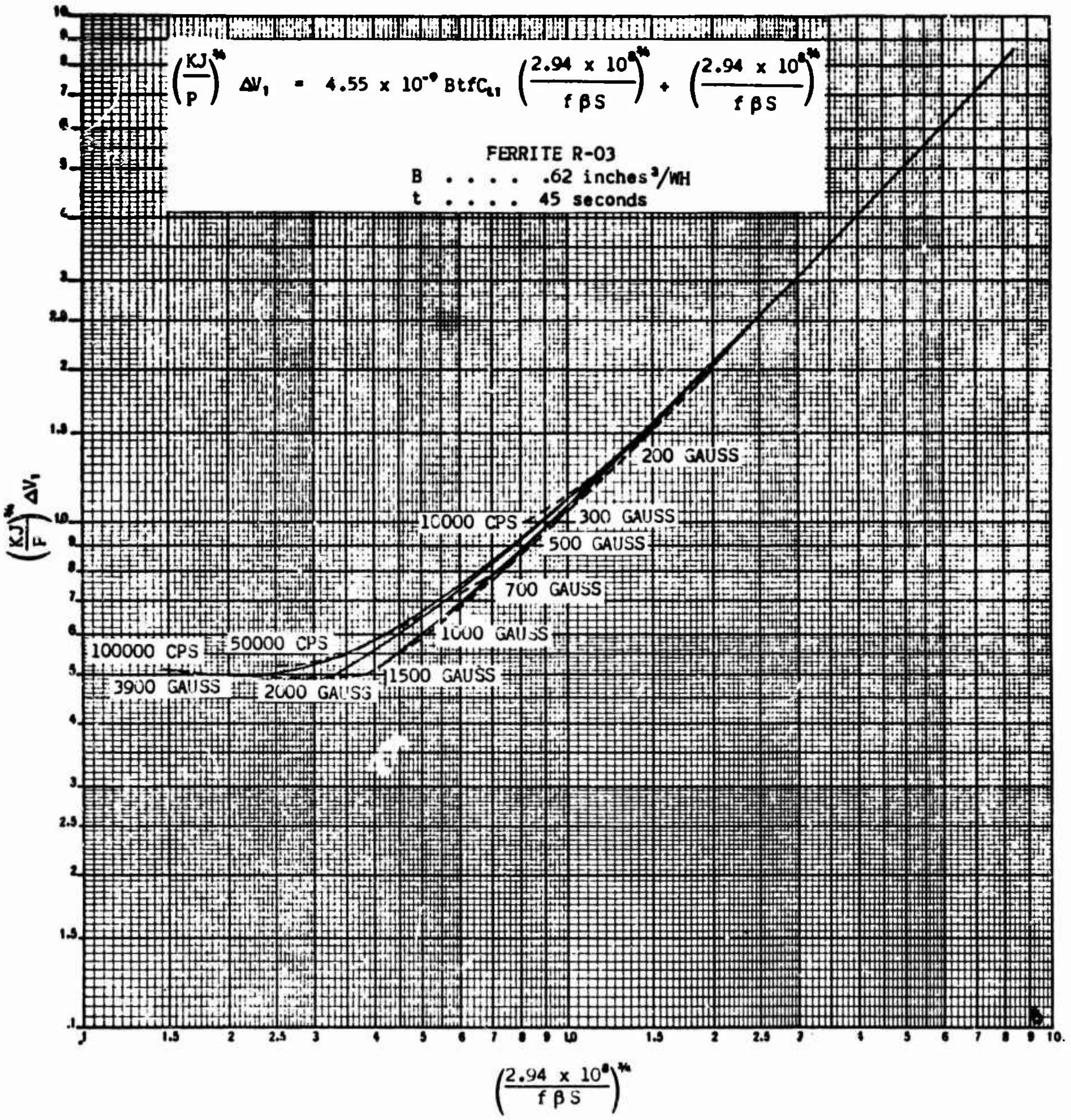


Figure 5 - EFFECT OF R-03 FERRITE ON SYSTEM VOLUME (B = .62 AND t = 45)

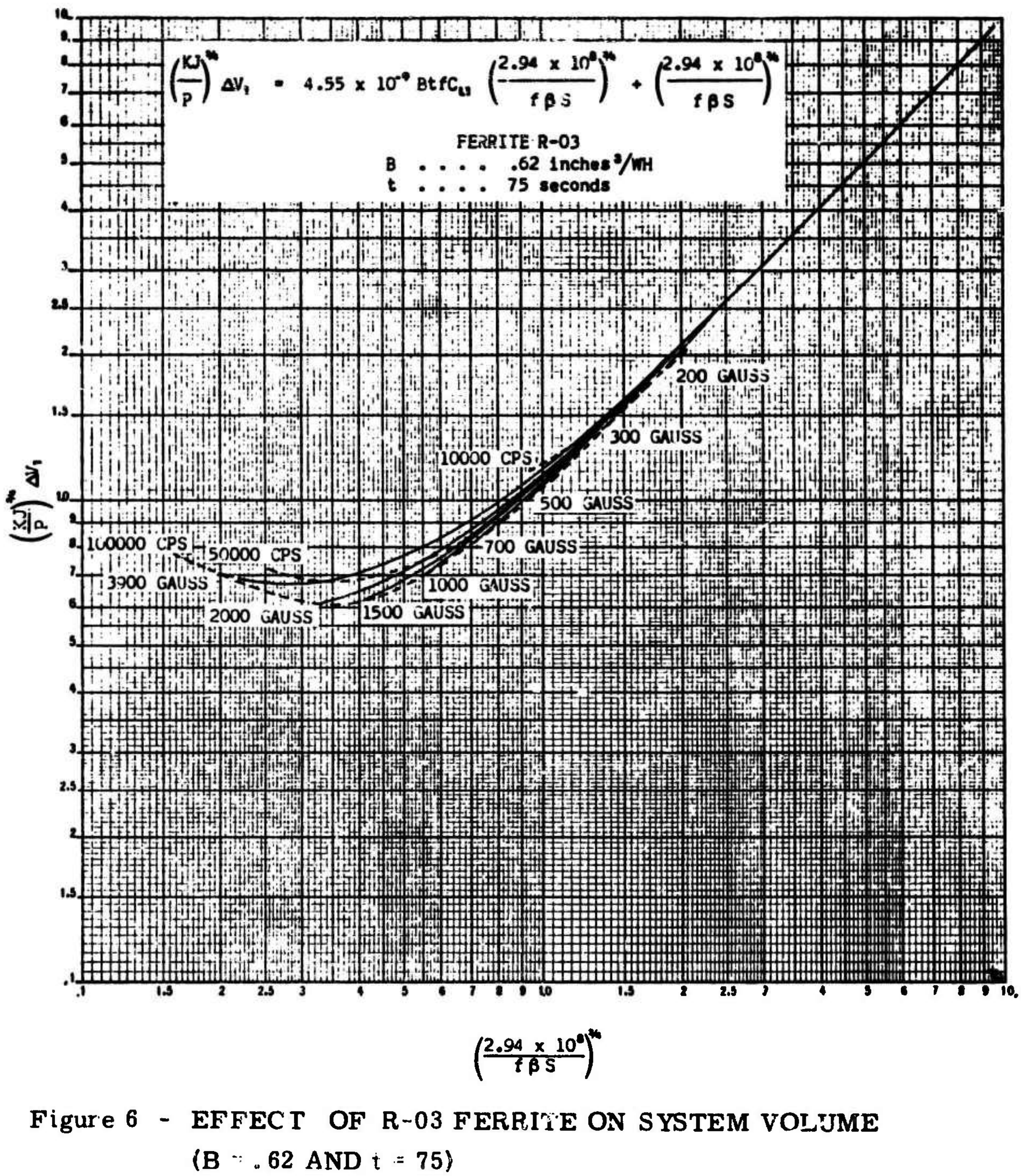


Figure 6 - EFFECT OF R-03 FERRITE ON SYSTEM VOLUME (B = .62 AND t = 75)

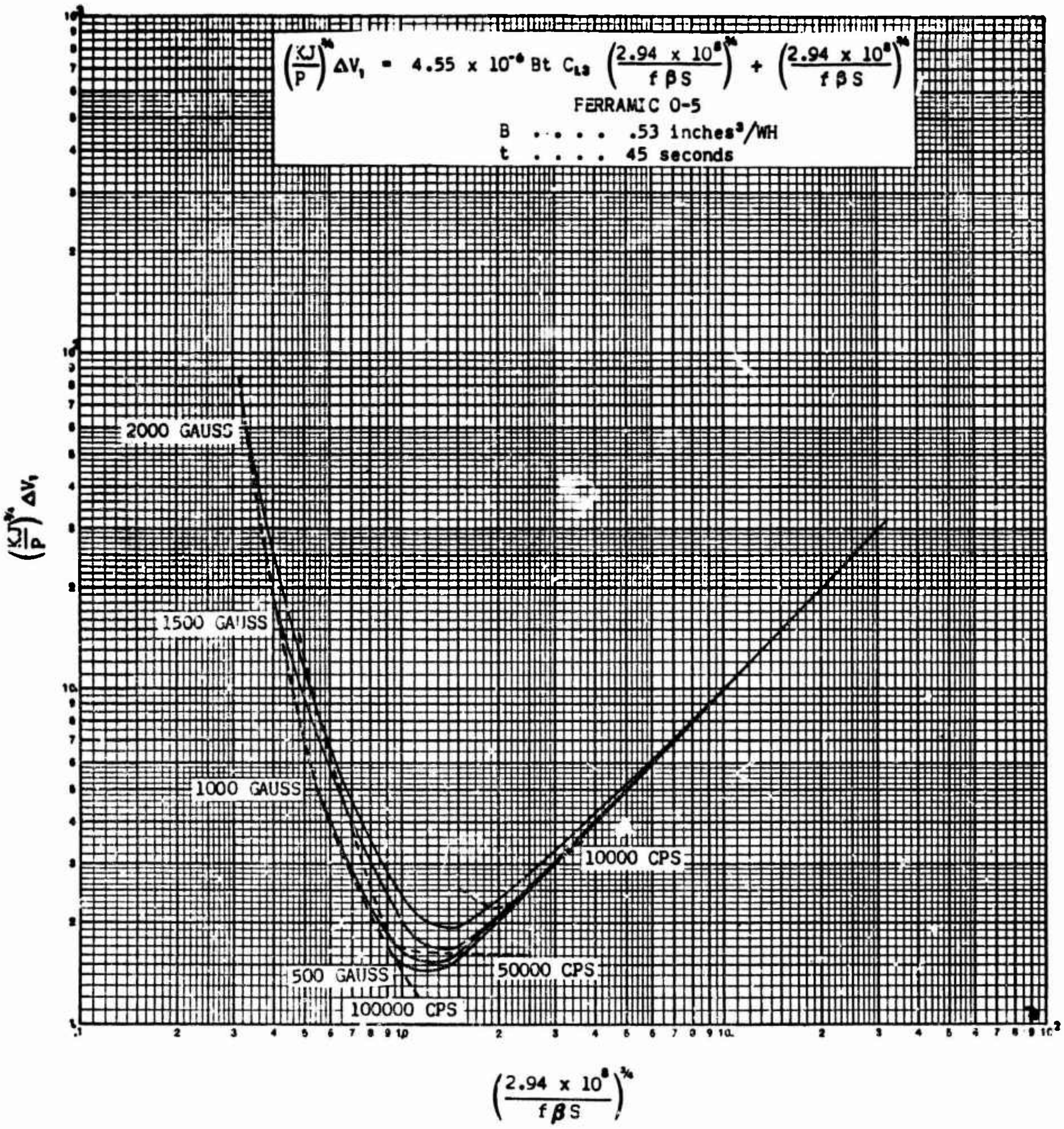


Figure 7 - EFFECT OF 0-5 FERRITE ON SYSTEM VOLUME (B = .53 AND t = 45)

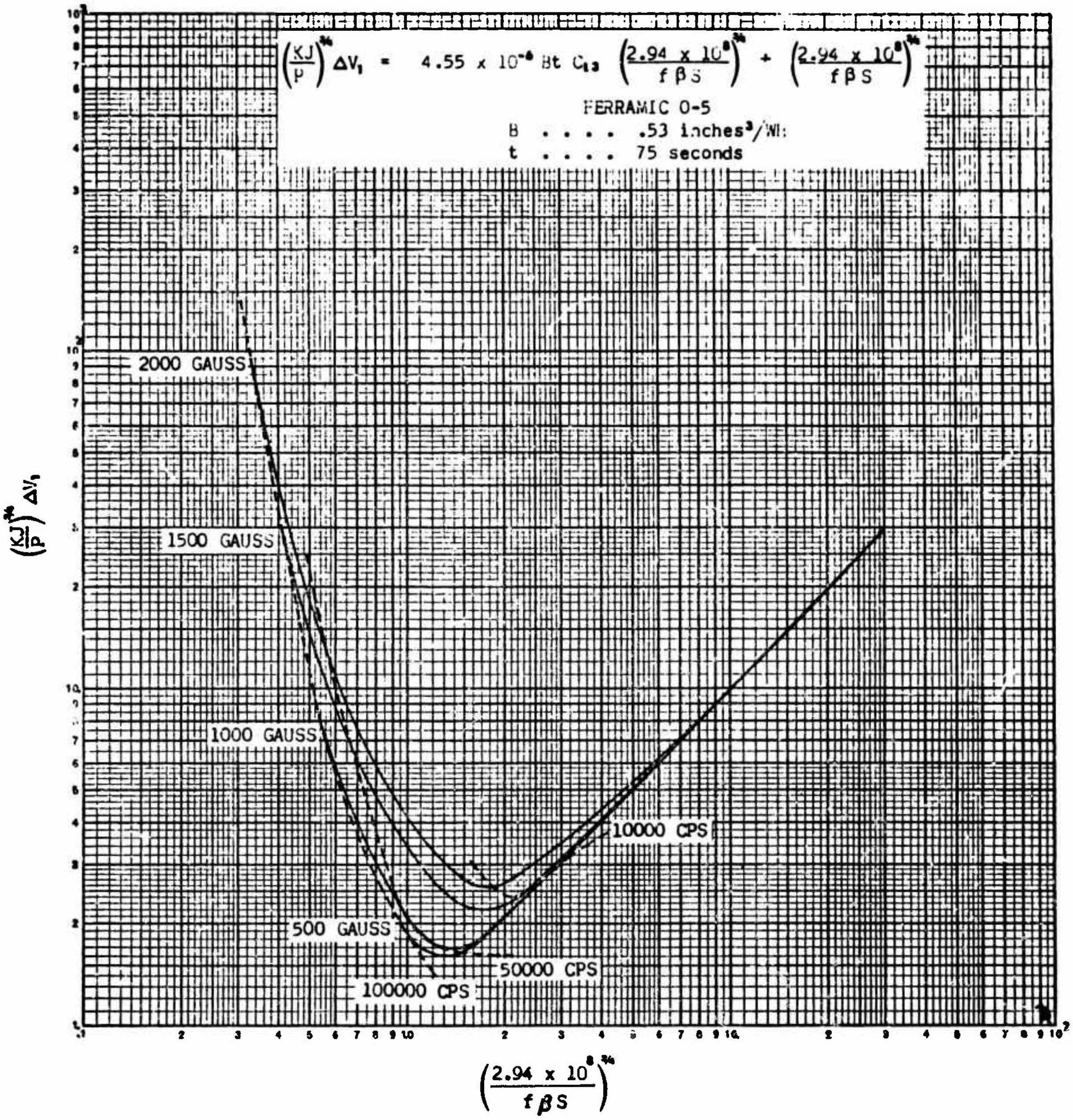


Figure 8 - EFFECT OF 0-5 FERRITE ON SYSTEM VOLUME (B = .53 AND t = 75)

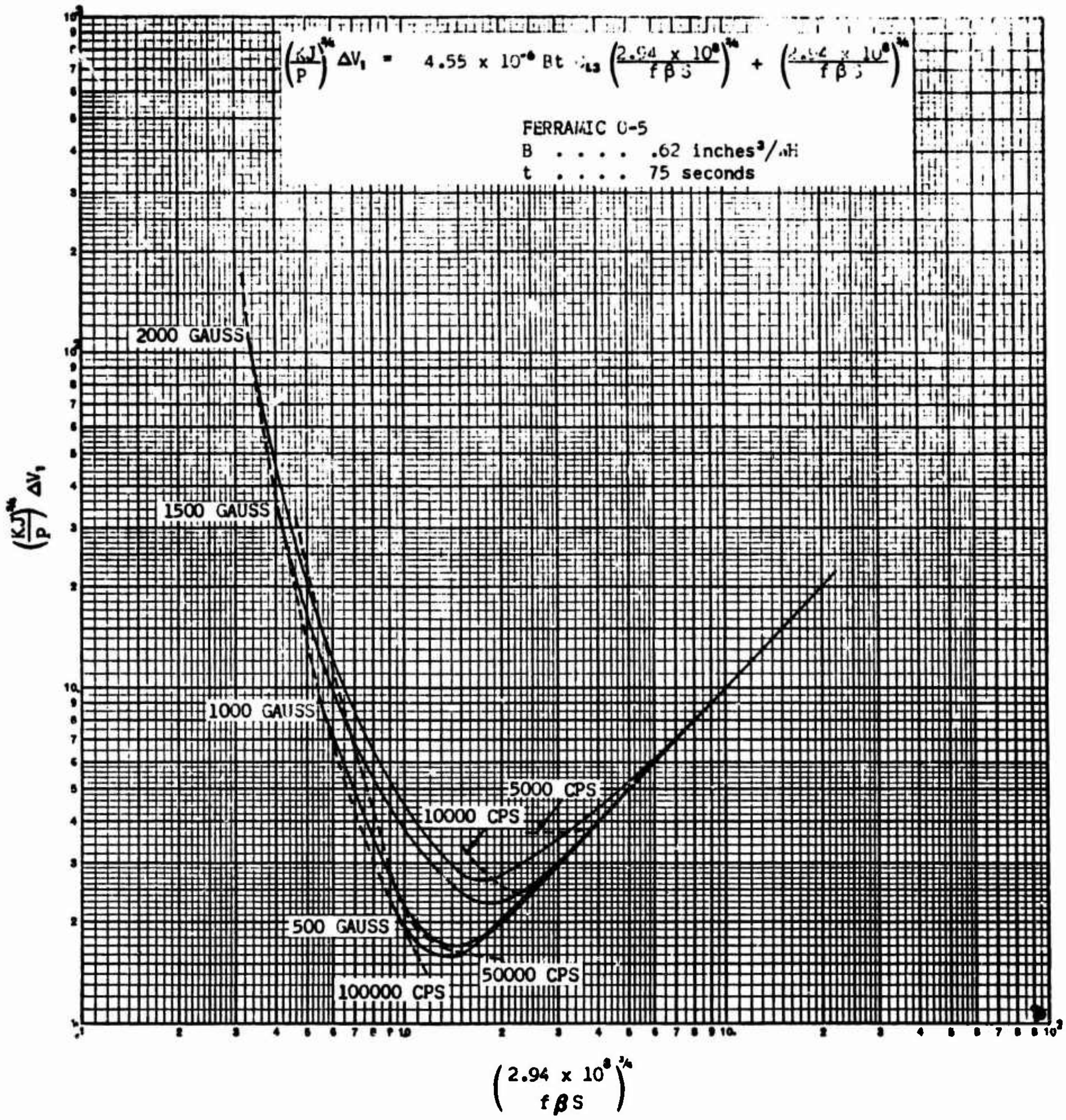


Figure 10 - EFFECT OF 0-5 FERRITE ON SYSTEM VOLUME (B = .62 AND t = 75)

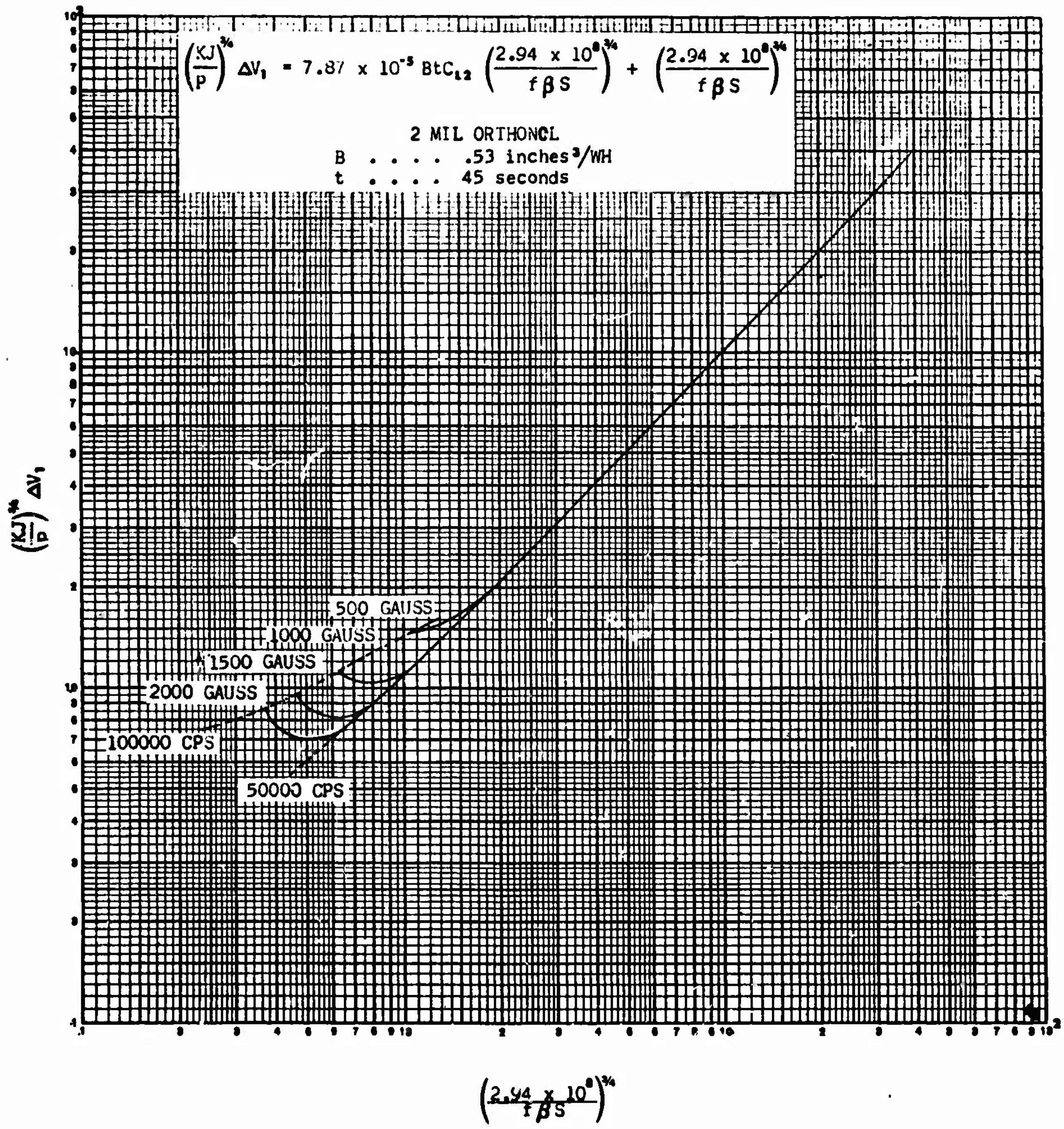


Figure 11 - EFFECT OF 2 MIL ORTHONOL ON SYSTEM VOLUME (B = .53 AND t = 45)

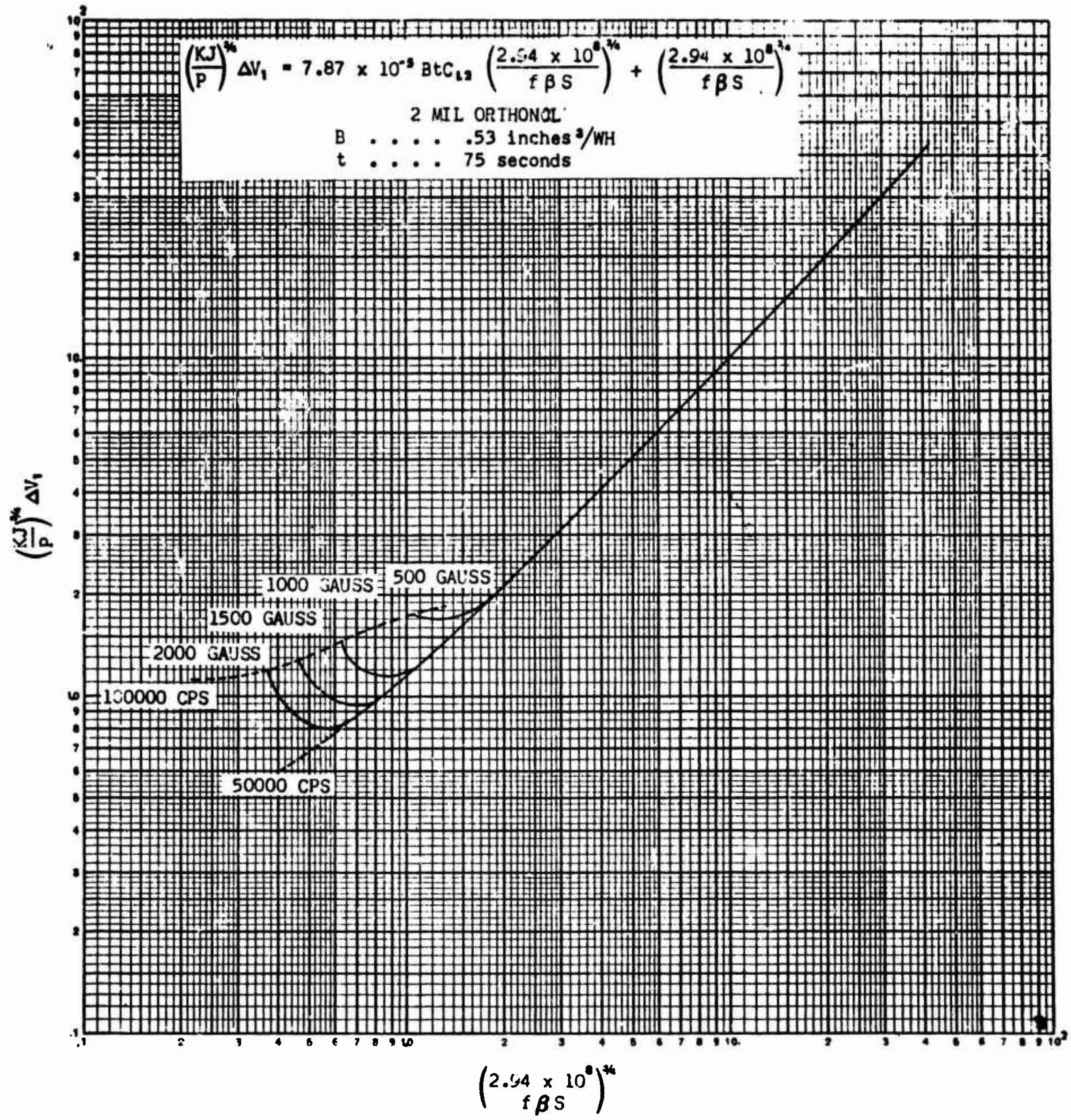


Figure 12 - EFFECT OF 2 MIL ORTHONOL ON SYSTEM VOLUME (B = .53 AND t = 75)

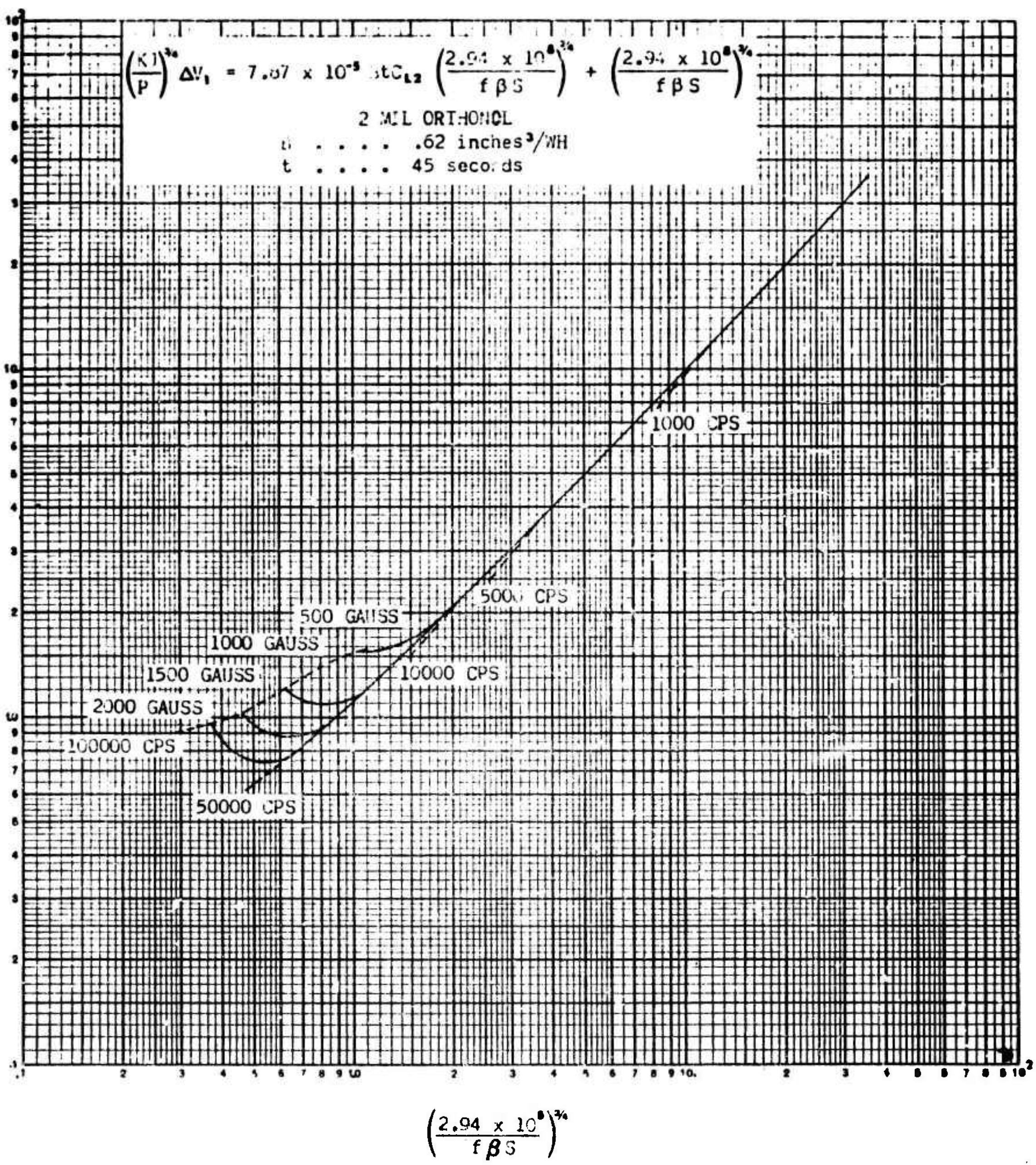


Figure 15 — EFFECT OF 2 MIL ORTHONOL ON SYSTEM VOLUME
(B .62 AND t 45)

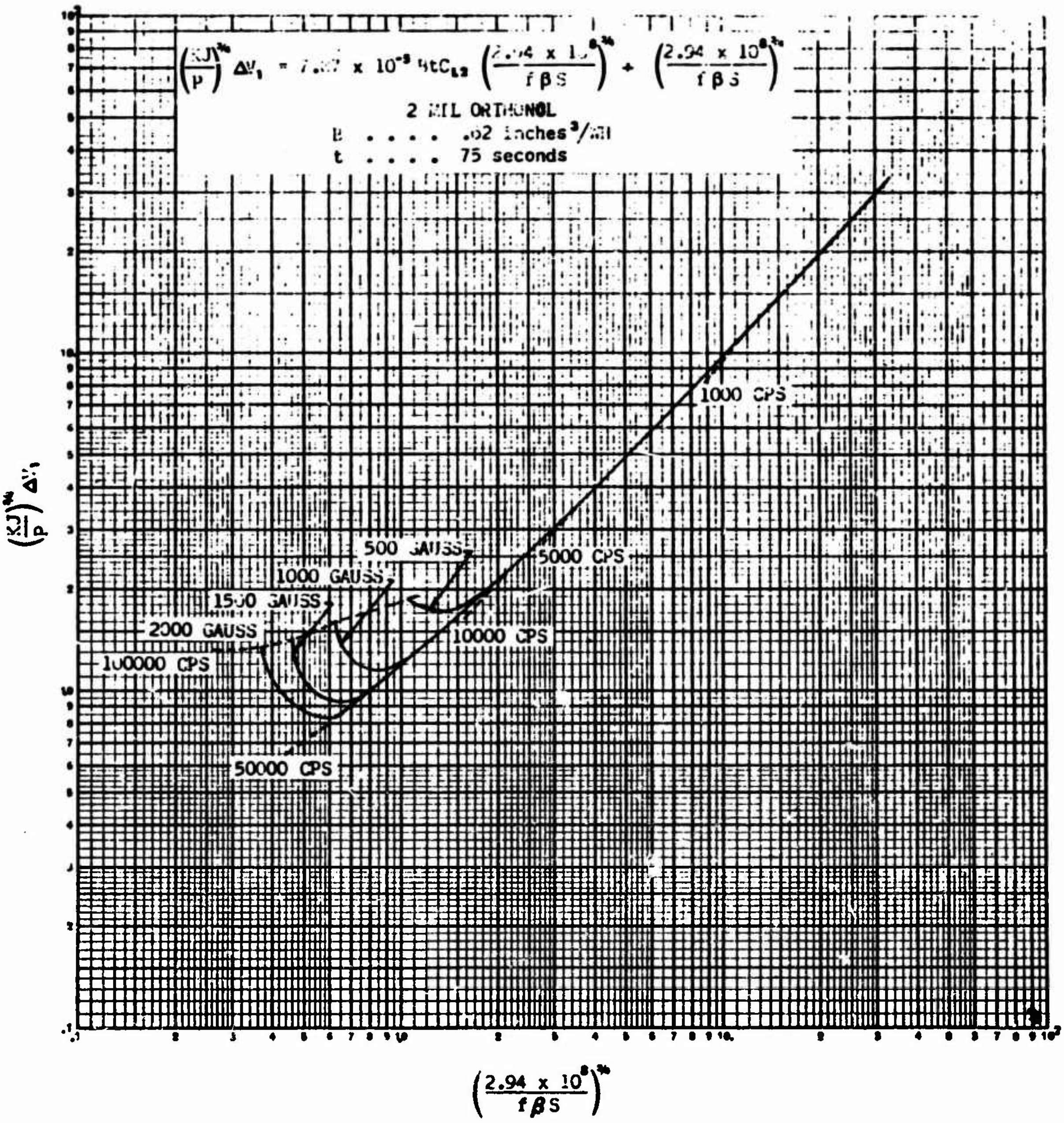


Figure 14 - EFFECT OF 2 MIL ORTHONOL ON SYSTEM VOLUME
(B = .62 AND t = 75)

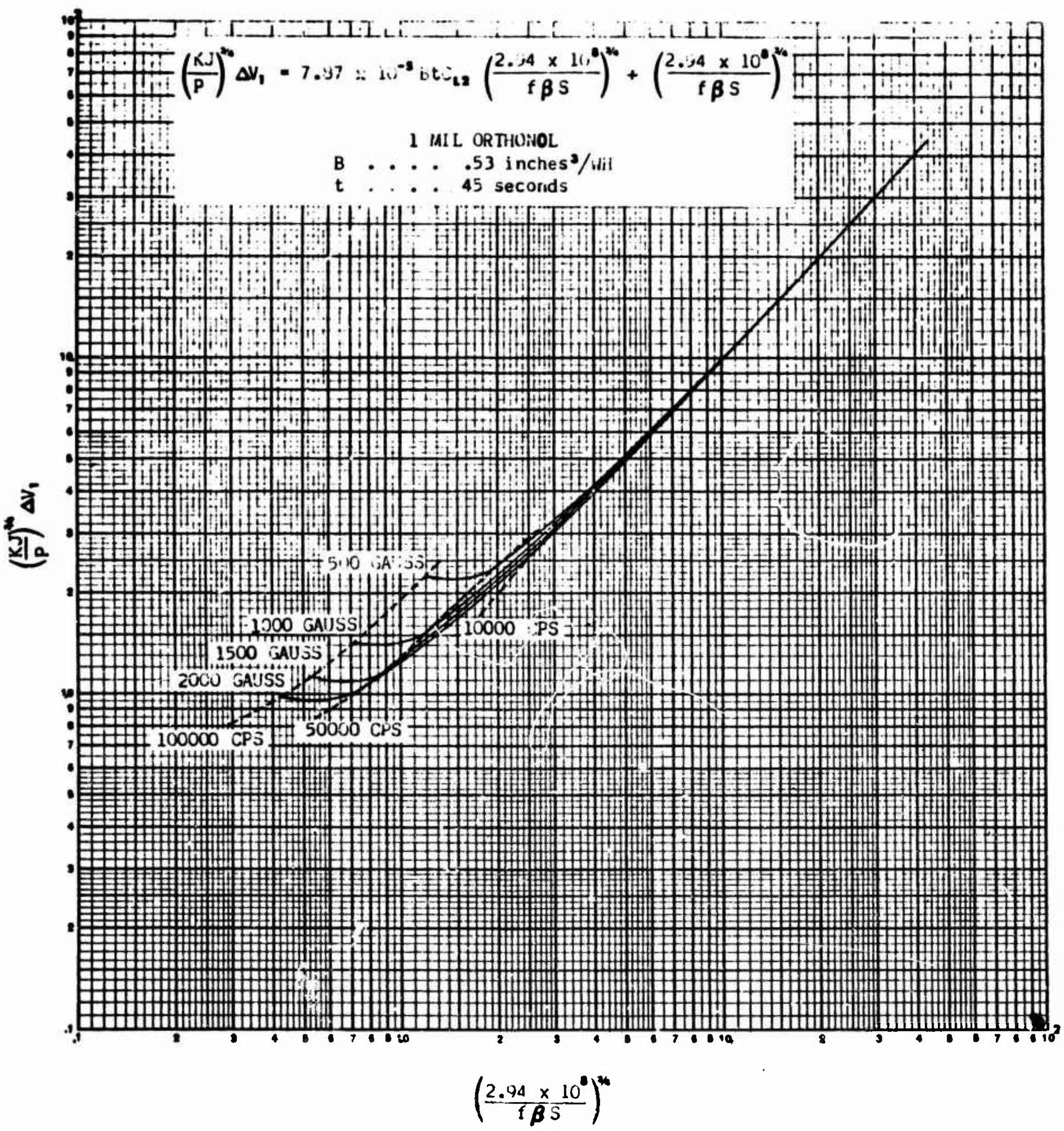


Figure 15 - EFFECT OF 1 MIL ORTHONOL ON SYSTEM VOLUME (B = .53 AND t = 45)

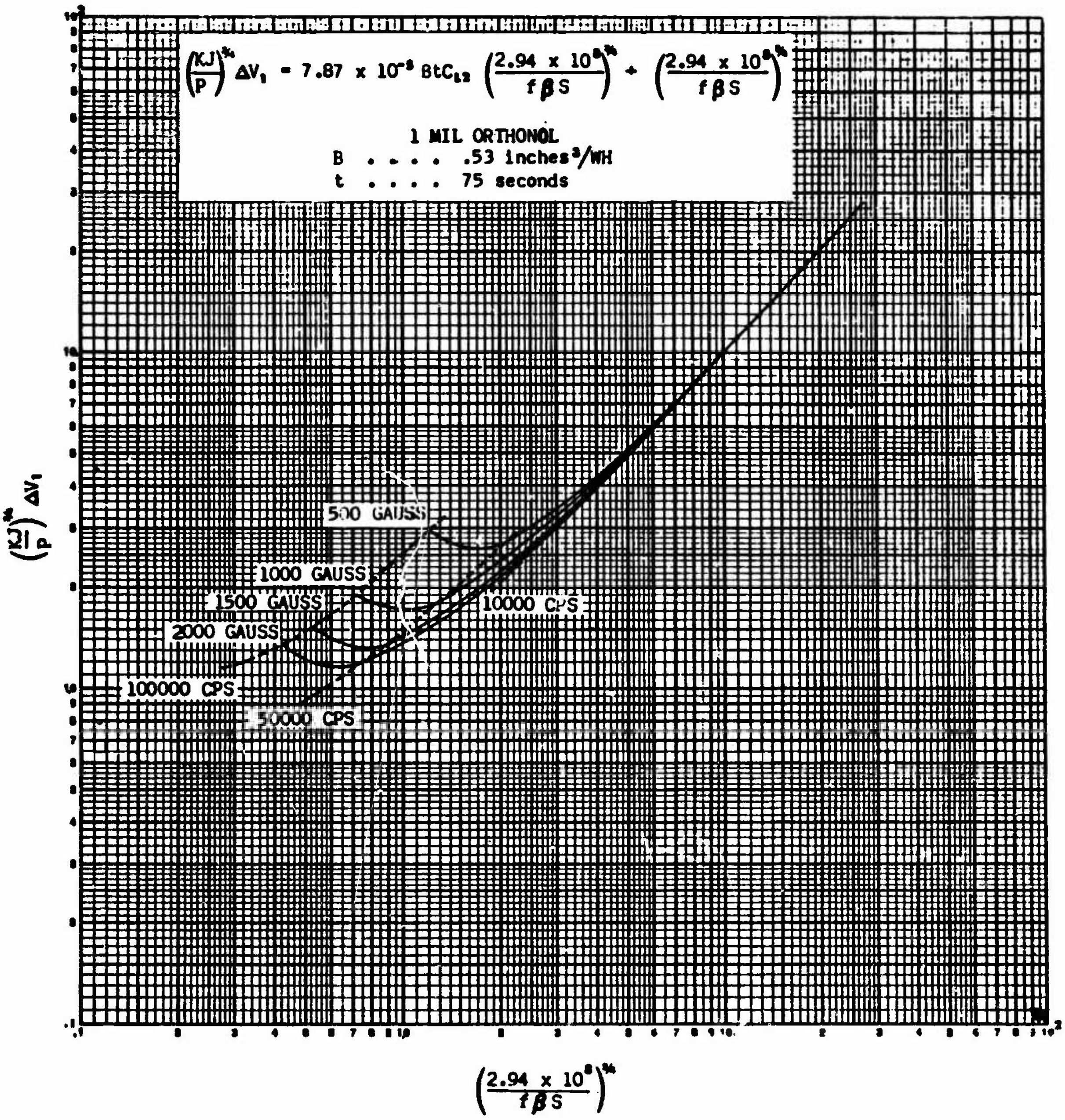


Figure 16 - EFFECT OF 1 MIL ORTHONOL ON SYSTEM VOLUME
(B = .53 AND t = 75)

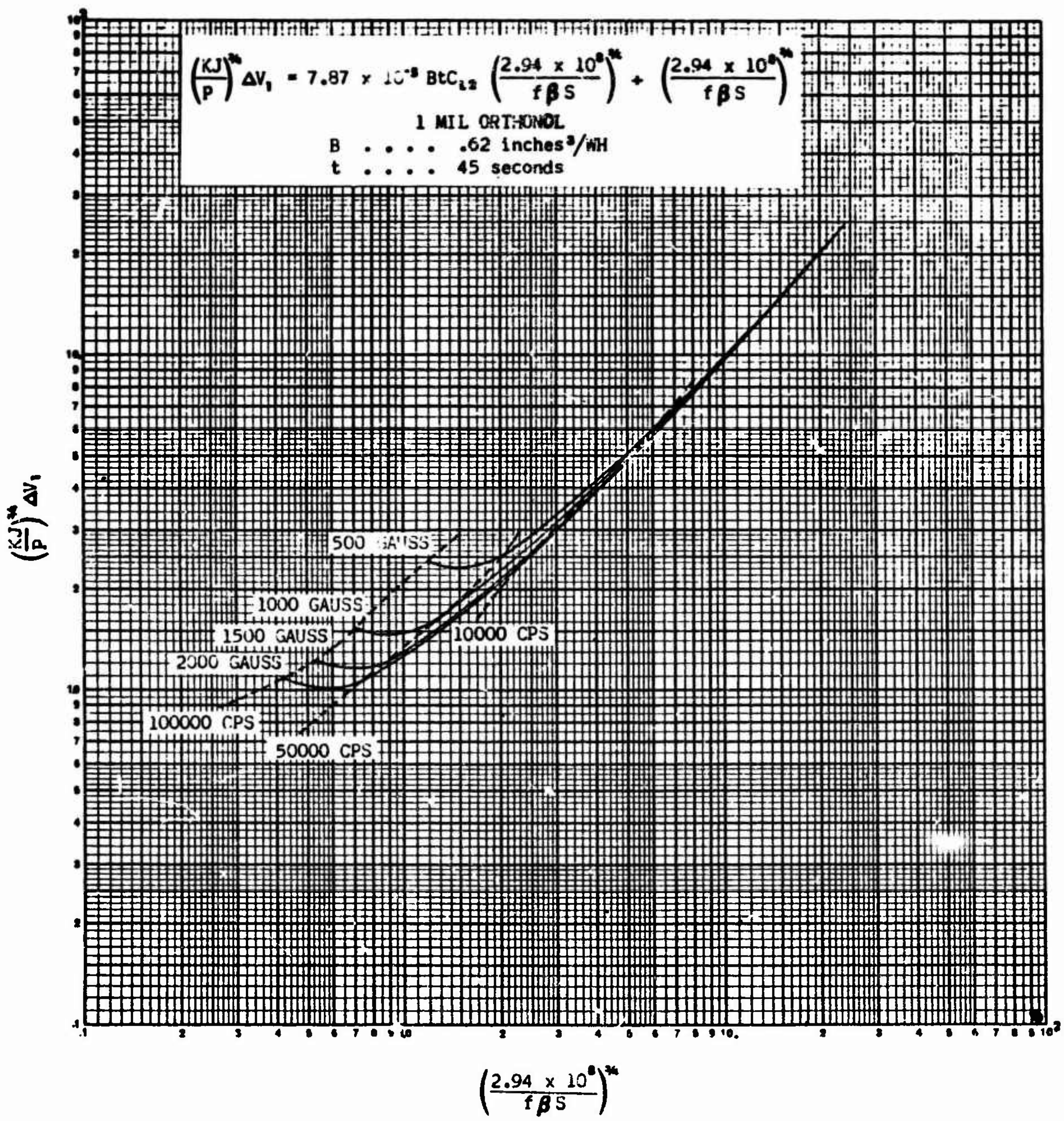


Figure 17 - EFFECT OF 1 MIL ORTHONOL ON SYSTEM VOLUME (B = .62 AND t = 45)

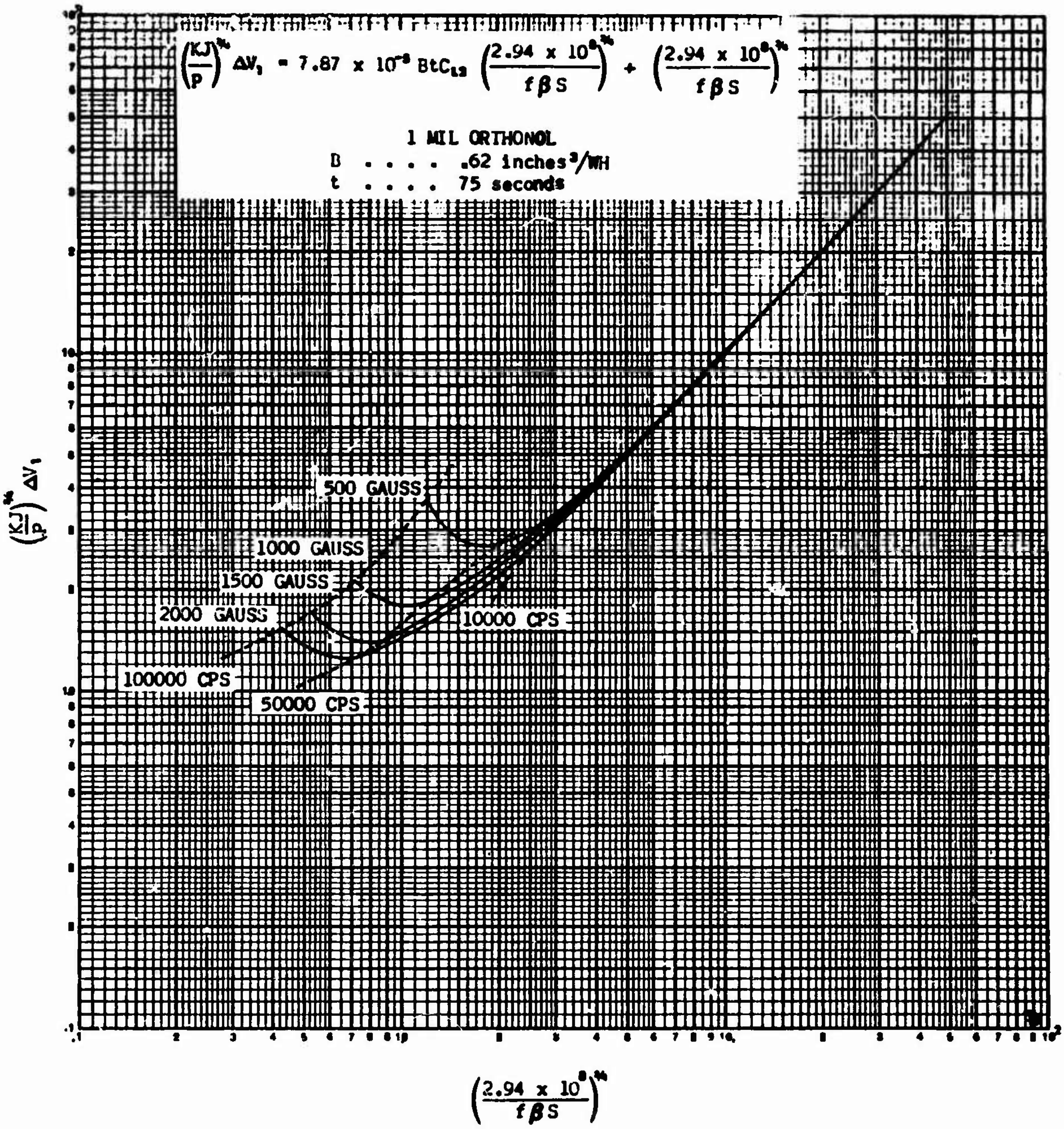


Figure 18 - EFFECT OF 1 MIL ORTHONOL ON SYSTEM VOLUME (B = .62 AND t = 75)

Assuming that no heat energy would be lost from the core material through radiation, convection, or conduction, the following general formula was derived for core temperature rise (Δ T)

$$\Delta T = (4.55 \times 10^{-9} f C_L) \frac{1}{C_{S'}} t$$

Where:

$C_{S'}$ = specific heat of the core material, in $\frac{\text{watt-hours}}{\text{in.}^3 \, °\text{C}}$

The rate of temperature rise, $\frac{\Delta t}{t}$, versus the product of $f\beta$ is plotted for R-03 ferrite in Figure 19.

The following expression was then derived to determine the increase in system volume, ΔT_2, due to adding a transformer winding.

$$\Delta T_2 = \left[\frac{(1.08 \times 10^{-10} T_1 + 2.53 \times 10^{-8})\, t\, J^2}{1 - .00696 \times 10^{-6}\, t\, J^2}\right] BK \left(\frac{2.66 \times 10^8 P}{f \beta S J K}\right)^{3/4} + \left(\frac{2.66 \times 10^8 P}{f \beta S J K}\right)^{3/4}$$

Where:

T_1 = Initial winding temperature, in °C.

This equation, the derivation of which is presented in Appendix B, assumes that no heat energy is lost from the winding through radiation, conduction, or convection.

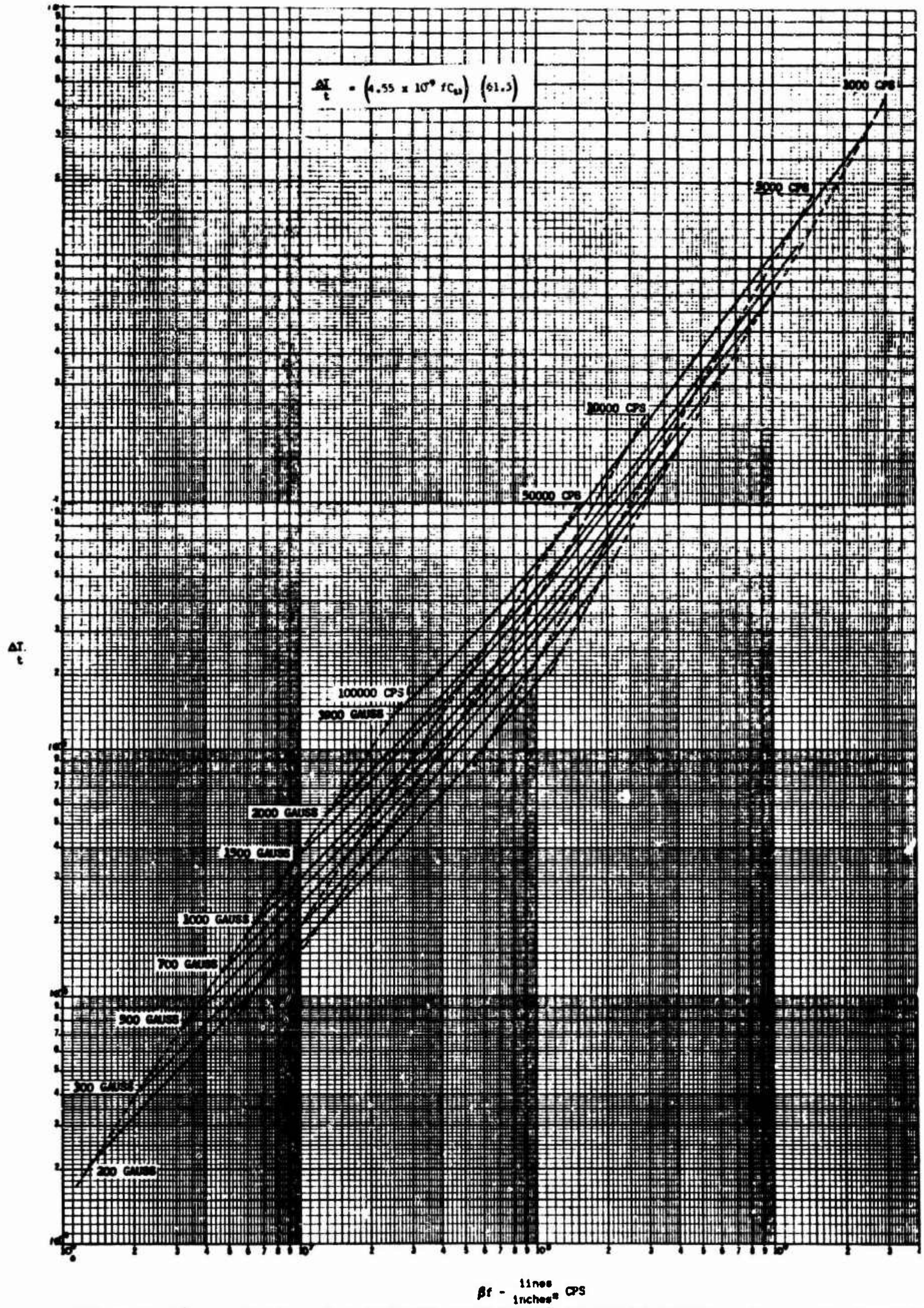


Figure 19 - RATE OF CORE TEMPERATURE RISE FOR R-03 FERRIT

Since the factors, f, θ, and S are largely dependent on the core material, and since the factor P is dictated by the application, these terms were transposed to the left side of the equation, as follows:

$$\left(\frac{f\,\theta\,S}{P}\right)^{3/4} \Delta V_2 = \left[\frac{\left(1.08 \times 10^{-10}\, T_1 + 2.53 \times 10^{-8}\right) t\, J^2}{1 - .00696 \times 10^{-6}\, t\, J^2}\right] BK$$

$$, \left(\frac{2.66 \times 10^{8}}{J K}\right)^{3/4} + \left(\frac{2.66 \times 10^{8}}{J K}\right)^{3/4}$$

With T_1 equal to 65°C (maximum specification requirement), B equal to 0.53 and 0.62 and t equal to 45 seconds and 75 seconds, a series of graphs of $\left(\frac{f\,\theta\,S}{P}\right)^{3/4} \Delta V_2$ versus J were plotted. These curves are presented in Figures 20 through 23.

Again assuming no heat energy loss from the winding through radiation, conduction, or convection, the following general formula was derived to describe temperature rise in the winding.

$$\Delta T = \frac{(6.96\, T_1 + 1630)\, J^2\, t}{10^9 - 6.96\, J^2\, t}$$

Curves of Δ T versus J for t equal to 45 seconds and 75 seconds, and with T_1 equal to 65°C, are presented in Figures 24 and 25.

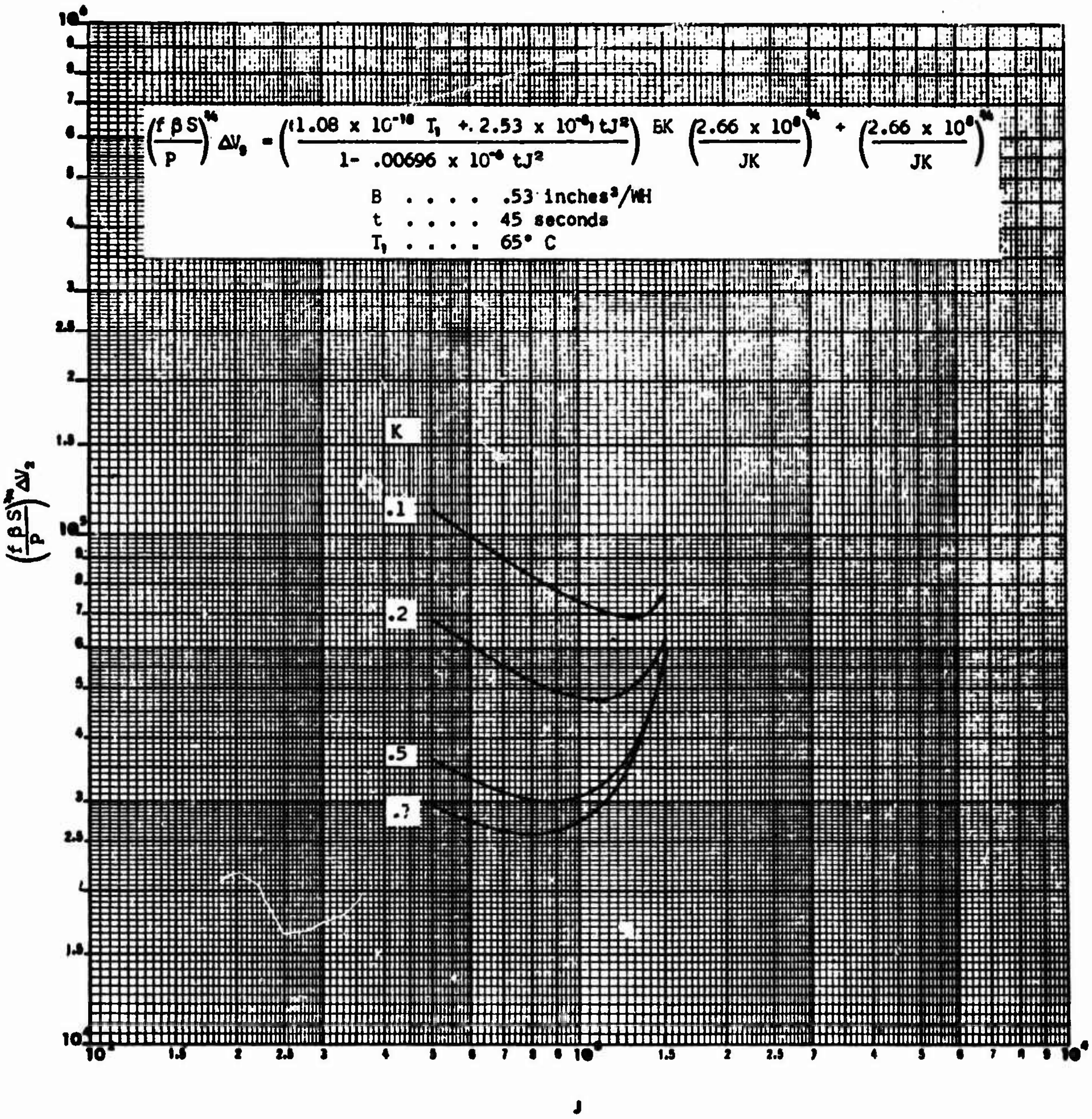


Figure 20 - EFFECT OF WINDING CURRENT DENSITY ON SYSTEM VOLUME (B = .53 AND t = 75)

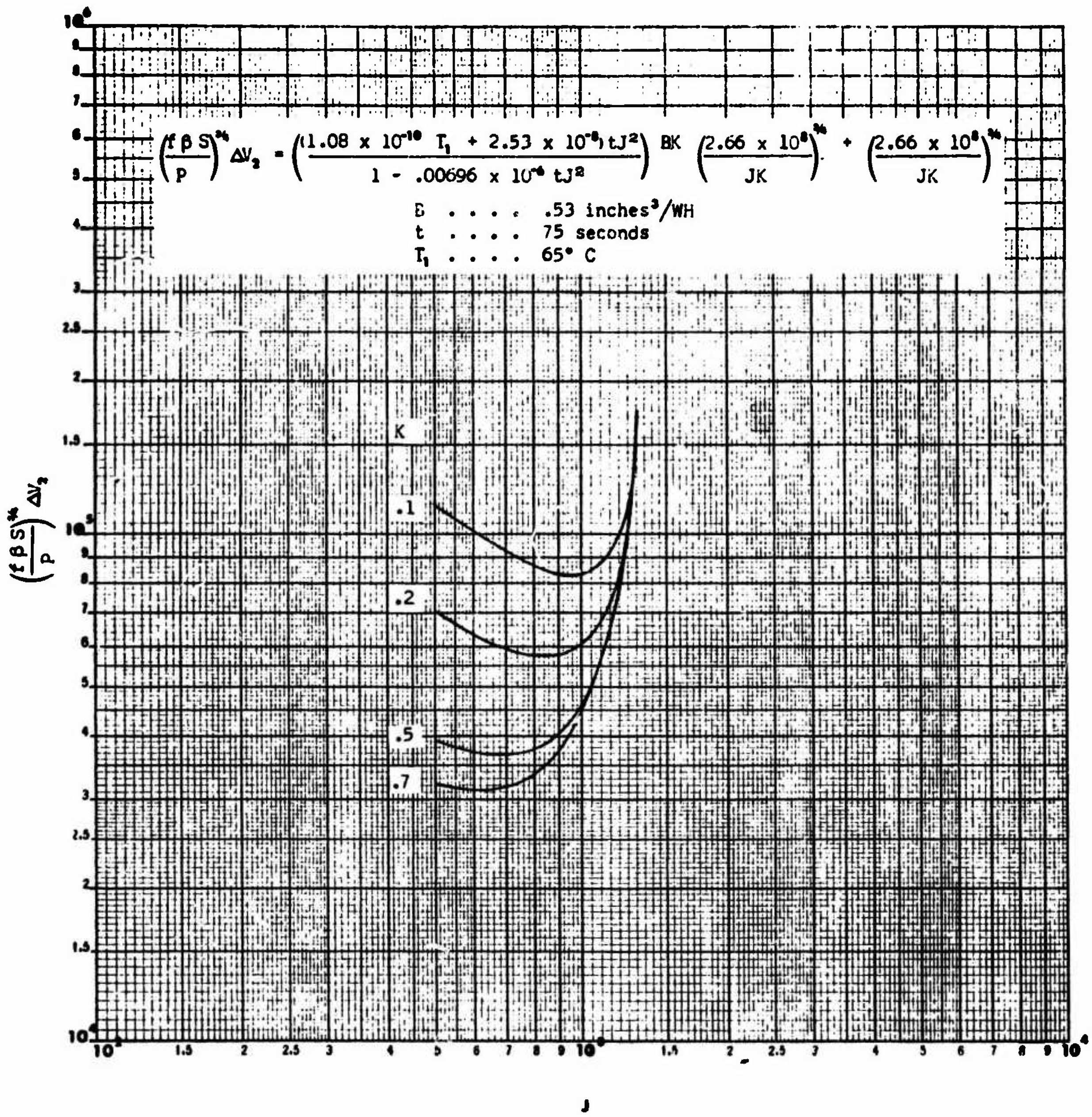


Figure 21 - EFFECT OF WINDING CURRENT DENSITY ON SYSTEM VOLUME (B = .53 AND t = 75)

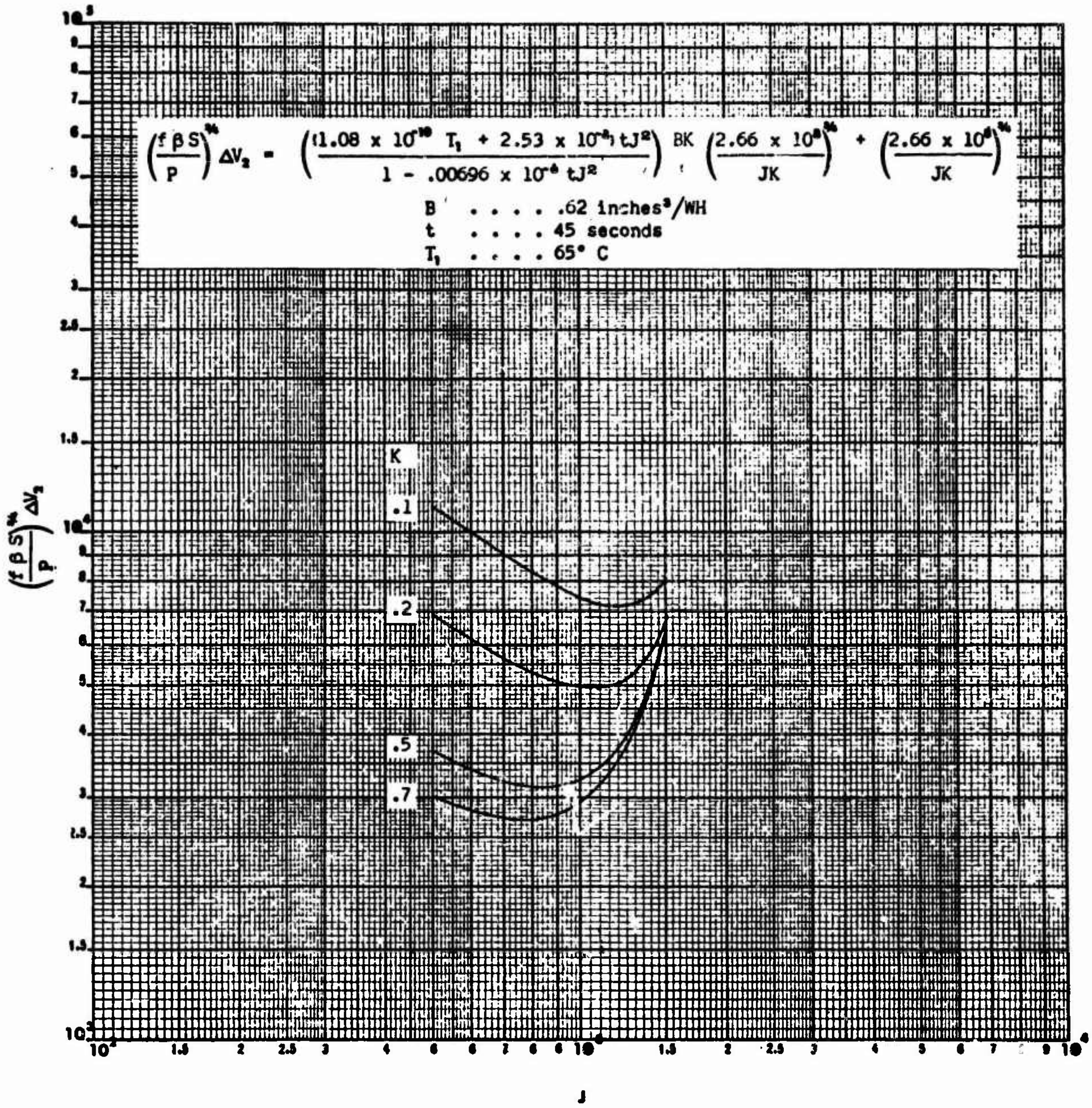


Figure 22 - EFFECT OF WINDING CURRENT DENSITY ON SYSTEM VOLUME (B = .62 AND t = 45)

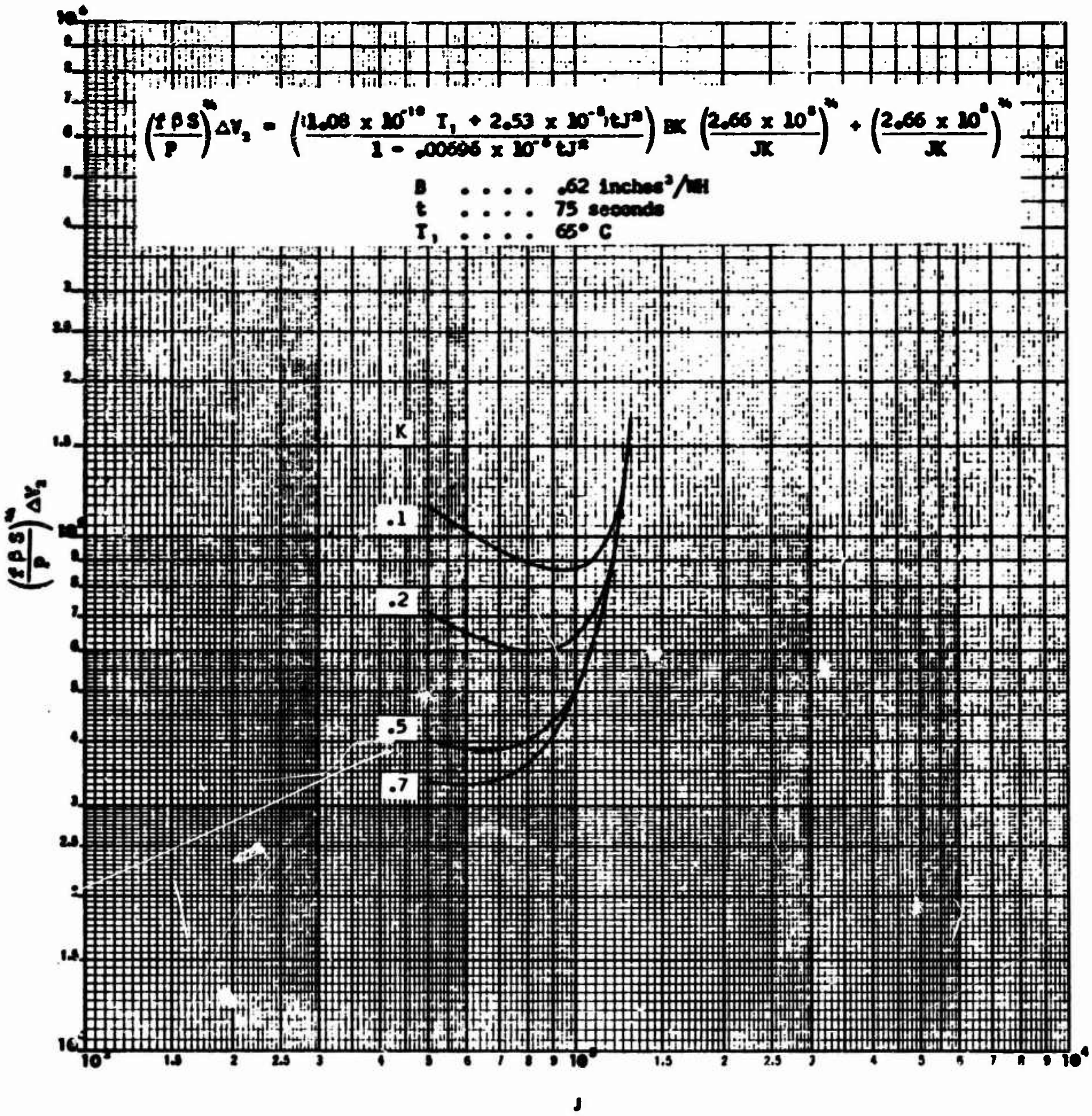


Figure 23 - EFFECT OF WINDING CURRENT DENSITY ON SYSTEM VOLUME (B = .62 AND t = 75)

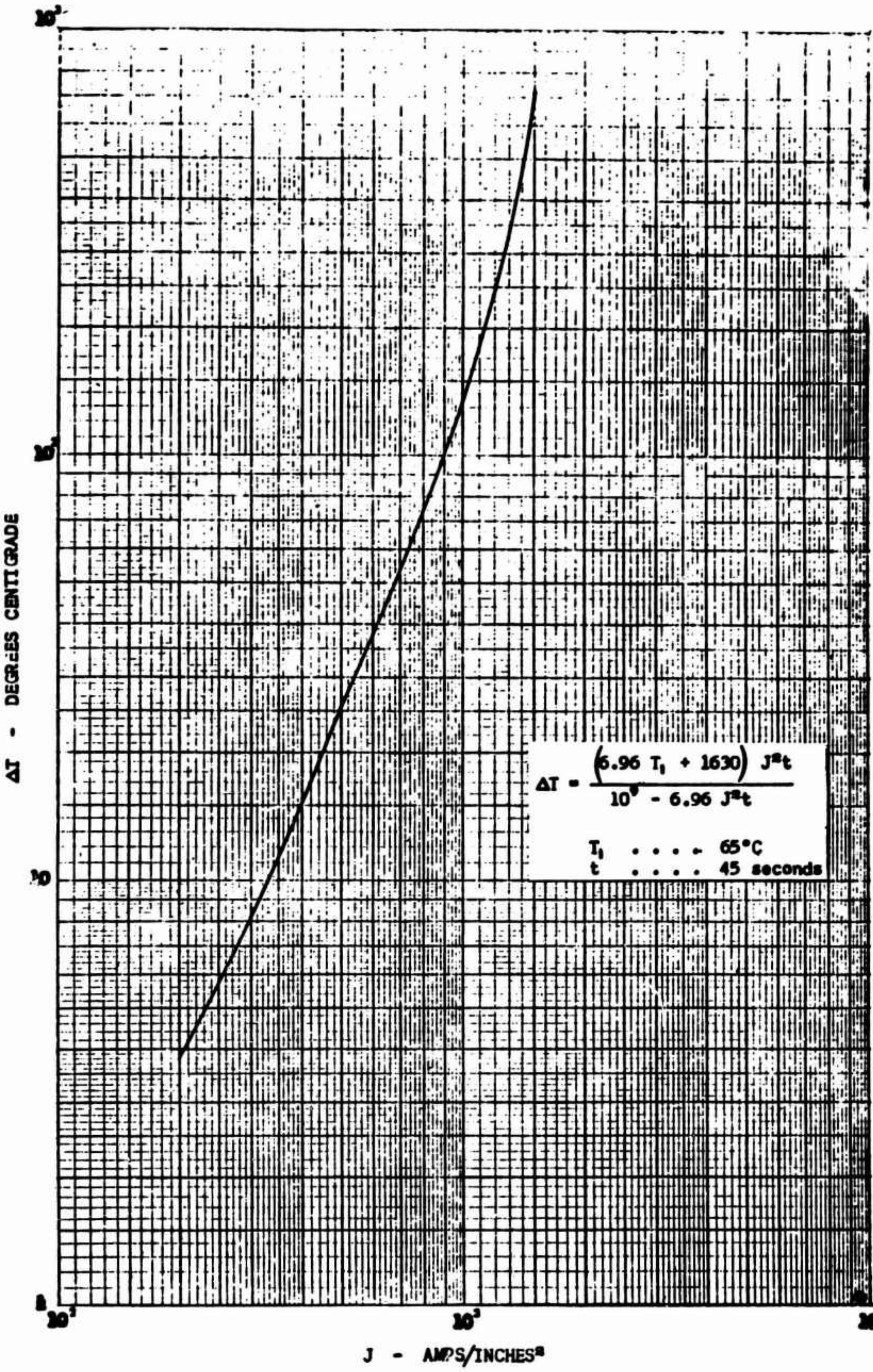


Figure 24 - WINDING TEMPERATURE RISE T_1 = 65 AND t = 45

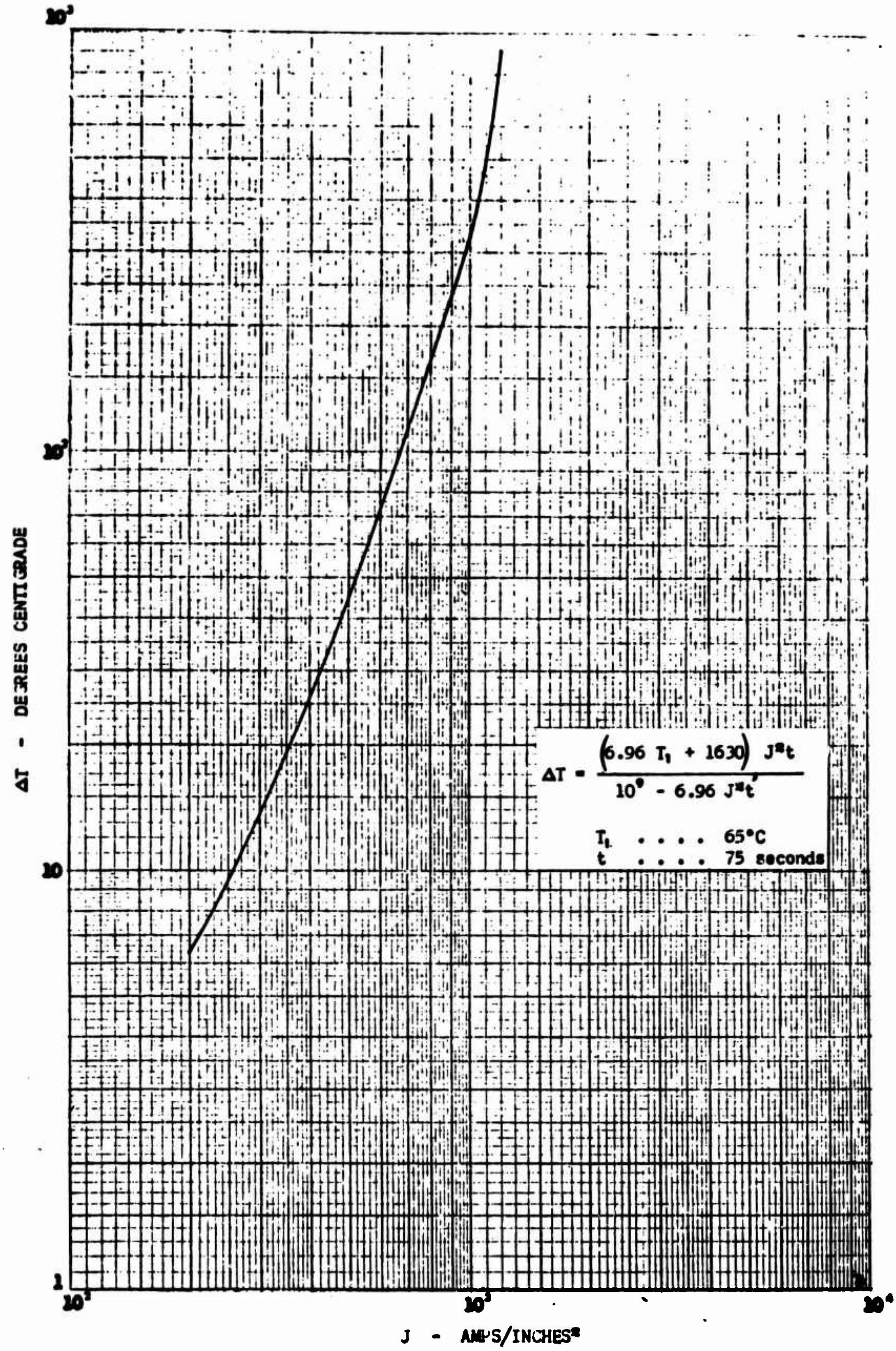


Figure 25 - WINDING TEMPERATURE RISE (T_1 = 65 AND t = 75)

3. TRANSISTOR SURVEY AND ANALYSIS

a. Transistor Survey

A letter was sent to transistor manufacturers requesting their recommendations for transistor types which could be used in a high-power dc/dc converter. A copy of the letter is presented in Appendix D.

Replies were received from Delco Radio, Continental Device Corp., RCA, Bendix, and National Semiconductor Corp. Continental Device Corp. does not make a suitable transistor. National Semiconductor Corp. has a fast-switching silicon transistor, but its current carrying capability is so low that it could not be used in high power devices.

The pertinent data received by the other four manufacturers are summarized in Table I (where there are blanks, the manufacturer was unable to supply data). These data are from specification sheets, and do not necessarily represent the values which would be obtained in a converter circuit. For example, the switching times can be improved by switching enhancement circuitry. Also, some of the higher-current transistors may be used somewhat below their maximum collector current ratings, to improve $V_{CE(SAT)}$ and switching times.

The RCA 2N3265 looks promising for high-power duty because of its exceptionally low $V_{CE(SAT)}$ for a silicon transistor. RCA did not suggest switching enhancement circuits, but the "typical" specification sheet values appear to be very good. The 150-volt. V_{CES} would require operation in a bridge circuit if a high input (battery) voltage were to be used.

TABLE I

SUMMARY OF TRANSISTOR DATA

MFR.	TYPE	MATERIAL	V_{CES} (VOLTS)	$V_{CE(SAT)}$ AT I_C	f_T (MC)	t_r (µS)	t_s (µS)	t_f (µS)	h_{FE} AT I_C	T_j(MAX)
RCA	2N3265	SILICON	150	0.75V AT 15A	20	0.5	1.5	0.5	25 AT 15A	200°C
BENDIX	2N1653	GERMONIUM	120	0.65V AT 25A		7.0	4.0	2.5	20 AT 20A	110°C
SOLITRON	2N3151	SILICON	150	1.5V AT 50A	20				10 AT 50A	200°C
DELCO	2N2581	SILICON	400	1.0V AT 10A		2.1	2.2	1.0	10 AT 10A	150°C

The Bendix 2N1653 is the only germanium transistor suggested by the manufacturers responding. Although the 2N1653 has the lowest $V_{CE(SAT)}$, it also has the longest switching time. Therefore, it should be considered only for comparatively low frequency operation. The lower temperature limit for germanium transistors also limits its use to a relatively short mission time(in the order of a few seconds); otherwise, the transistors will overheat. The low collector voltage rating will require bridge circuit operation when relatively high battery voltages are used.

The Solitron 2N3151 has the largest current-carrying capability and a reasonably high f_T. Switching times were not given in the specifications, but should be comparable to the other silicon transistors in the table. The V_{CES} maximum of 150 volts limits the application of the 2N3151 to bridge circuit operation, as in the above two cases. The comparatively high $V_{CE(SAT)}$ and low gain at the characterization point of 50 amperes collector current suggests the use of this transistor at lower collector currents, perhaps 25 amperes. The case size of this transistor is larger than the previous three, which detracts from the advantage of a high current rating when total transistor volume is considered.

Delco Radio recommended a high voltage silicon transistor, the 2N2581. This transistor appears to be particularly attractive at high input voltage levels. Among the responding manufacturers, only Delco recommended switching circuits, and suggested switching times which could be achieved in a high power level circuit. For this reason, the 2N2581 characteristics were used in the following examples of transistor loss calculations.

b. Transistor Analysis

Presented in the following paragraphs is an analysis of a suitable transistor for an 8.2-kw converter for the missile power supply. This analysis

examines the relationship between transistor power losses and transistor parameters. There are two categories of power losses: switching losses and conduction losses. Switching losses are related to three components: rise time (t_R), storage time (t_S), and fall time (t_F). These components are illustrated in Figure 26.

By using equation (4) from Appendix C, and by substituting the values given in Figure 26, each switching power loss is calculated as follows:

The rise time switching loss is calculated as:

$$P_{RT} = ft_R \left[\frac{1}{6} (2V_S I_S + 0) + \frac{1}{3} (0 + 0)\right]$$

To simplify the equation the rise time switching loss may be calculated as

$$P_{RT} = ft_R \frac{V_S I_S}{3} \qquad (1)$$

In the above equation, the values substituted from Figure 26 are:

$$t_1 = t_S$$
$$V_x = 2V_S$$
$$V_y = 0$$
$$I_x = 0$$
$$I_y = I_S$$

The storage time switching loss is calculated as:

$$P_{ST} = ft_S \left[\frac{1}{6} \left(0 + 2V_S I_S \left(\frac{t_S}{t_S + t_F}\right)\right) + \frac{1}{3} \left(2V_S I_S \left(\frac{t_S}{t_S + t_F}\right) + 0\right)\right]$$

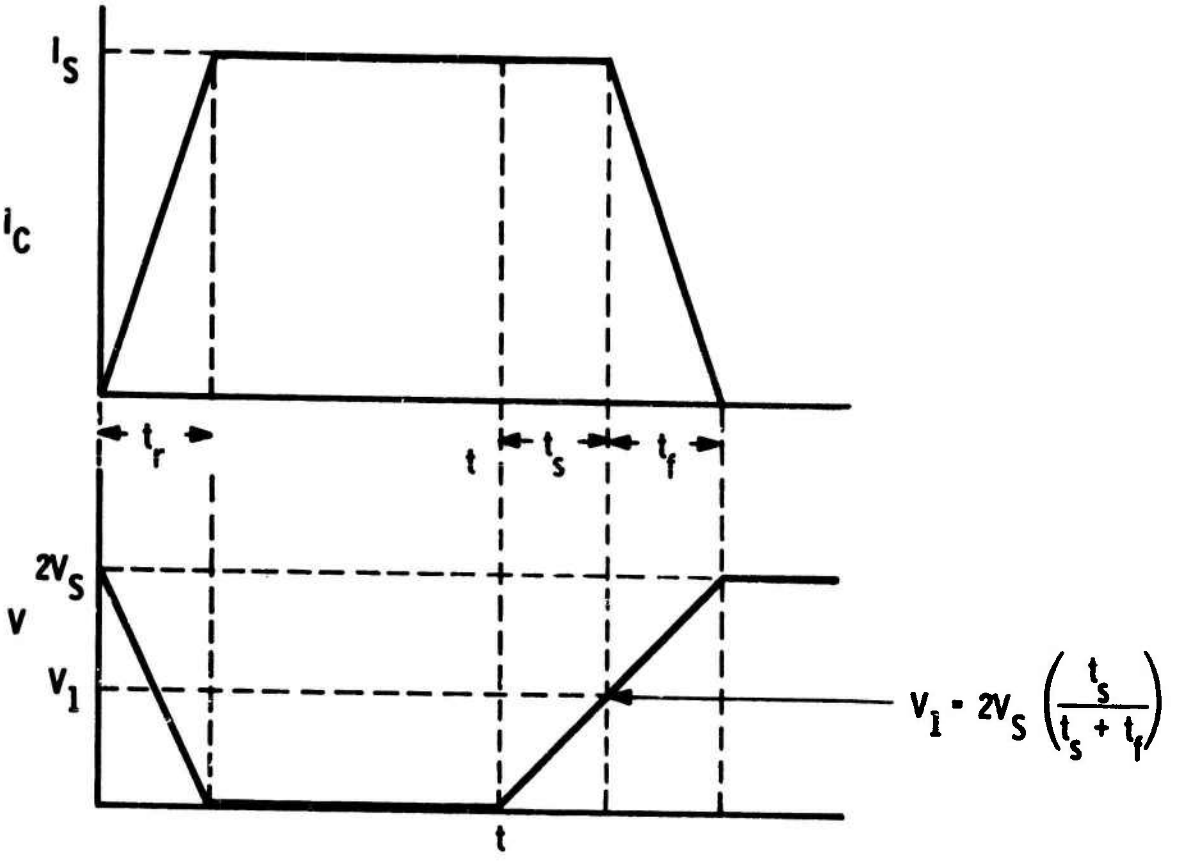


Figure 26 - SWITCHING LOSS COMPONENTS

To simplify, the storage time switching loss may be calculated as:

$$P_{ST} = ft_S \left[V_S I_S \left(\frac{t_S}{t_S + t_F} \right) \right] \qquad (2)$$

In the above equation, the values substituted from Figure 26 are:

$t_1 = t_S$

$V_x = 0$

$V_y = 2V_S \left(\frac{t_S}{t_S + t_F} \right)$

$I_x = I_S$

$I_y = I_S$

The fall time switching loss is calculated as:

$$P_{FT} = ft_F \left[\frac{1}{6} (0 + 2\, V_S I_S) + \frac{1}{3} (2V_S I_S \left(\frac{t_S}{t_S + t_F} \right) + 0) \right]$$

To simplify the equation, the fall time switching loss may be calculated as:

$$P_{FT} = ft_F \left(\frac{V_S I_S}{3} \right) \left[1 + 2 \left(\frac{t_S}{t_S + t_F} \right) \right] \qquad (3)$$

In the above equation, the values substituted from Figure 26 are:

$t_1 = t_F$

$V_x = 2V_S \left(\frac{t_S}{t_S + t_F} \right)$

$V_y = 2V_S$

$I_x = I_S$

$I_y = 0$

The switching losses defined by equations (1), (2), and (3) above are combined as follows:

$$P_{SW} = P_{RT} + P_{ST} + P_{FT}$$

Substituting from equations (1), (2), and (3);

$$P_{SW} = ft_R\left(\frac{V_S I_S}{3}\right) + ft_S\left[V_S I_S\left(\frac{t_S}{t_S + t_F}\right)\right] + ft_F\left(\frac{V_S I_S}{3}\right)\left[1 + 2\left(\frac{t_S}{t_S + t_F}\right)\right]$$

The combined switching losses may be simplified as follows:

$$P_{SW} = f\,V_S I_S\left\{\left(\frac{t_R}{3}\right) + \left(\frac{t_S{}^2}{t_S + t_F}\right) + \left(\frac{t_F}{3}\right)\left[1 + 2\left(\frac{t_S}{t_S + t_F}\right)\right]\right\} \quad (4)$$

Thus, the total switching loss is directly proportional to the converter oscillator frequency, the battery terminal voltage and current, and the three switching time parameters. As shown in the preceding example, equation (4) will assist in selecting transistors that will minimize these power losses.

Transistor conduction losses are comprosed of two components: "on" losses and "off" losses. Assuming operation at saturation, the "on" loss is:

$$P_{ON} + \left[V_{CE(SAT)}\,I_S + V_{BE}\left(\frac{I_S}{h_{FE}}\right)\right] \quad (5)$$

Similarly, the "off" loss is:

$$P_{OFF} = (2V_S\, I_{CO} + V_{EBO}\, I_{EBO}) \tag{6}$$

Combining the two conduction losses and averaging:

$$P_{CON} = \left(\frac{P_{ON} + P_{OFF}}{2} \right)$$

Substituting from equations (5) and (6):

$$P_{CON} = \frac{\left[V_{CE(SAT)}\, I_S + V_{BE}\left(\frac{I_S}{h_{FE}} \right) \right] + (2V_S\, I_{CO} + V_{EBO}\, I_{EBO}}{2}$$

To simplify, the total conduction loss may be written as follows:

$$P_{CON} = \left[\frac{I_S\left[V_{CE(SAT)} + \left(\frac{V_{BE}}{h_{FE}} \right) \right] + (2V_S\, I_{CO} + V_{EBO}\, I_{EBO})}{2} \right] \tag{7}$$

Combining equations (4) and (7), the total average transistor power loss is:

$$P_{T(AVG)} = P_{SW} + P_{CON}$$

Substituting:

$$P_{T(AVG)} = f\, V_S\, I_S \left\{ \left(\frac{t_R}{3} \right) + \left(\frac{t_S{}^2}{t_S + t_F} \right) + \left(\frac{t_F}{3} \right) \left[1 + 2\left(\frac{t_S}{t_S + t_F} \right) \right] \right\}$$
$$+ \left\{ \frac{I_S\left[V_{CE(SAT)} + \left(\frac{V_{BE}}{h_{FE}} \right) \right] + \left(2V_S I_{CO} + V_{EBO} I_{EGO} \right)}{2} \right\} \tag{8}$$

As shown by the above example, equation (8) can be used to select a specific transistor capable of minimizing converter power losses in a specific system.

As shown in Appendix C, any transistor power loss increases the overall system volume by requiring additional battery volume to compensate for this power loss; i.e., $\Delta V_2 = \left(\frac{Bt}{3600}\right) P_{T(AVG)}$.

Figure 27 illustrates the relationship between battery volume, in cubic inches, and converter oscillator frequency. A typical battery terminal voltage (100 volts) and current (10 amperes) were chosen; the switching time parameters for both light and heavy saturation operation modes were taken from the 2N2581 transistor specification. Also, power transfer durations (t) of 45 and 75 seconds were selected.

As an example of how the battery volume is affected by the oscillator frequency, refer to Figure 27. A 25-kc oscillator frequency requires a battery volume, per transistor, of from 0. 137 cubic inch to 0. 184 cubic inch for a 45-second power transfer duration, but the battery volume requirement is increased to a range from 0. 330 cubic inch to 0. 450 cubic inch for a 75-second power transfer duration. The precise requirement for battery volume, within the ranges specified in Figure 27, depends on the operational mode of the transistor.

4. SYSTEM VOLUME ANALYSIS

Four power supply system configurations have been investigated with respect to battery volume requirements, as follows:

- A separate battery supplying each load independently.
- A separate battery and converter-regulator combination supplying each load independently.

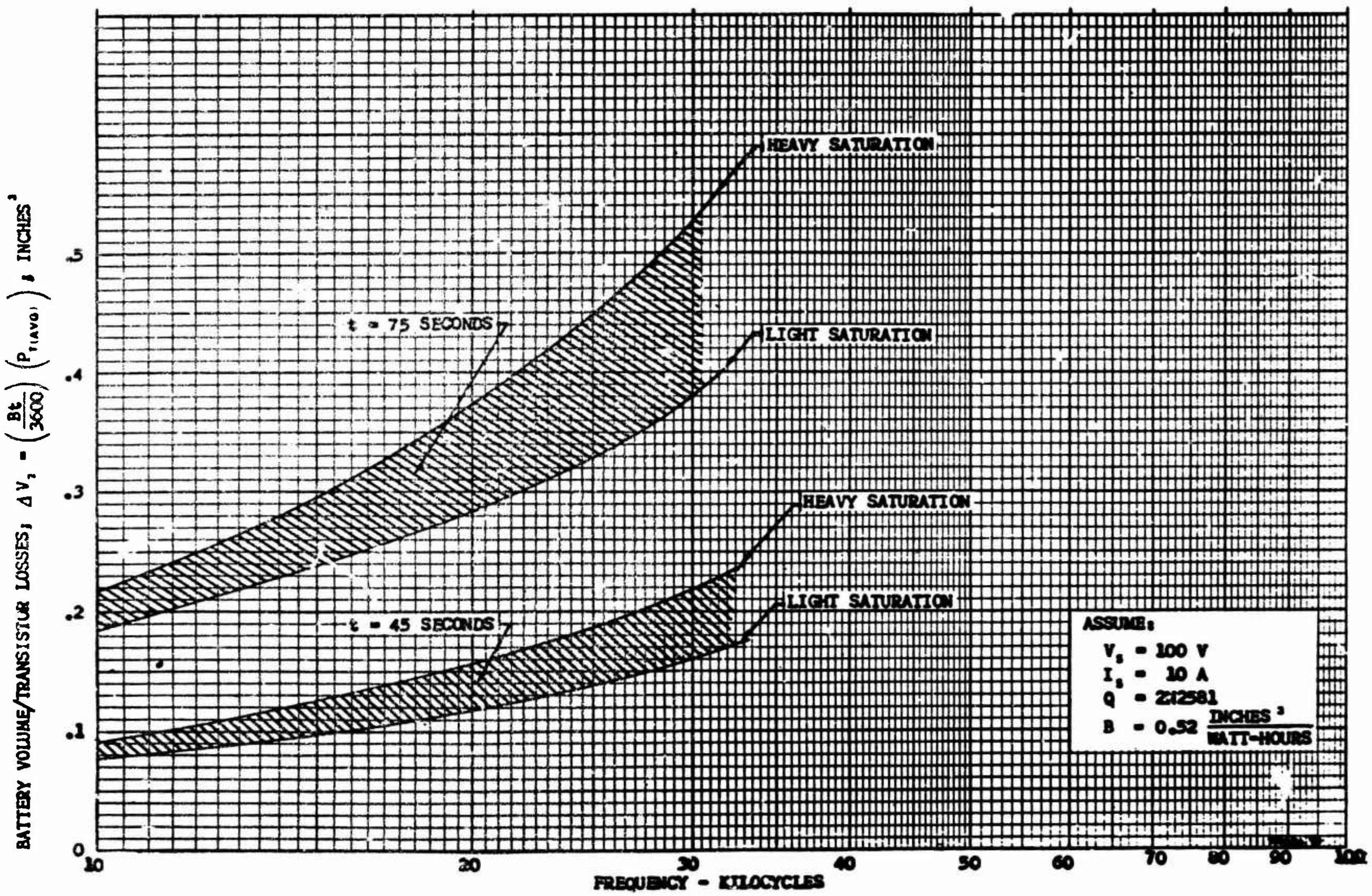


Figure 27 - EFFECT OF OSCILLATOR FREQUENCY ON BATTERY VOLUME

- One battery supplying the 6. 3-volt floating load and one battery supplying the remaining loads.

- One battery and converter-regulator combination supplying all loads.

Using the formulae derived for battery volume, the volume of a power supply comprised of separate batteries supplying each load directly was calculated. The results are shown in Table II.

TABLE II

REQUIRED BATTERY VOLUME FOR SPECIFIED POWER SUPPLY LOADS

POWER SUPPLY LOADS	VOLUME OF BATTERY SUPPLYING LOAD DIRECTLY (cu. -in.)
+6. 3 volts, 10% regulation, 9 amps, 75-second duration	2. 497
+6. 3-volts floating, 10% regulation, 2 amps, 75-second duration	1. 930
+90 volts, 10% regulation, 15 amps, 45-second duration	35. 660
-3000 volts, 3% regulation, 1. 25 amps, 45-second duration	875. 600
-1500 volts, 10% regulation, 2 amps, 75-second duration	458. 700
+50 volt, 3% regulation, 0. 25 amp, 45-second duration	14. 120
+10 volts, 3% regulation, 2 amps, 45-second duration	2. 990
-200 volts, 3% regulation, 0. 1 amp, 45-second duration	56. 190
TOTAL VOLUME	1447. 687

During the course of another study we examined how a combination of a battery and a converter-regulator would affect the battery volume. In a battery converter-regulator combination, the battery would have to supply enough energy to satisfy the losses in the converter. Therefore, the energy term, R, in the battery volume equation becomes R/Nc, where Nc = converter efficiency.

In a converter-regulator, the output voltage can be maintained within a very narrow range while the input voltage varies over a relatively wide range. It was assumed all power supply voltage regulation requirements could be met in a converter-regulator-battery combination, with the voltage regulation of the battery equal to 15%.

For each load requirement, a family of curves was plotted which compared battery volume and battery terminal voltage. Each curve in the family is for a different value of converter efficiency (Nc). The curves are presented in Figures 28 through 35.

During a third study we assumed that two batteries would supply all the loads. One battery supplied the 6.3-volt floating load; another battery supplied the remaining loads. The formula for determining the battery volume required for servicing the 6.3-volt floating load is:

Vol (6.3-volt floating-load battery)

$$= 0.28V + 0.62R \text{ at } \pm 10\% \text{ regulation}$$

$$= 0.28 \times 6.3 + \frac{0.62 \times 6.3 \times 2 \times 75}{3600}$$

$$= 1.765 + 0.1625$$

$$= 1.9275 \text{ inches}^3$$

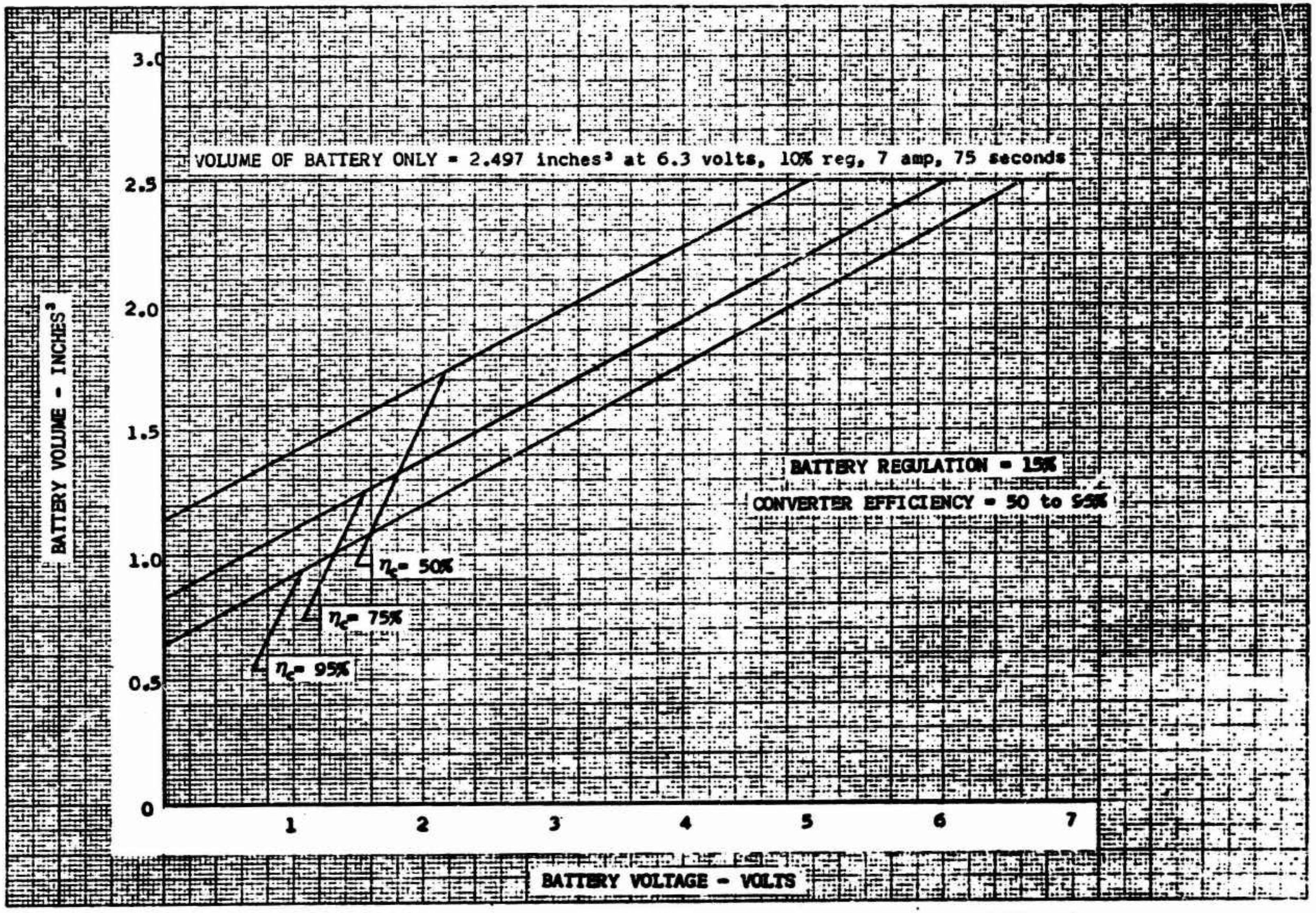


Figure 28 - BATTERY VOLTAGE VS BATTERY VOLUME (6.3 VOLTS)

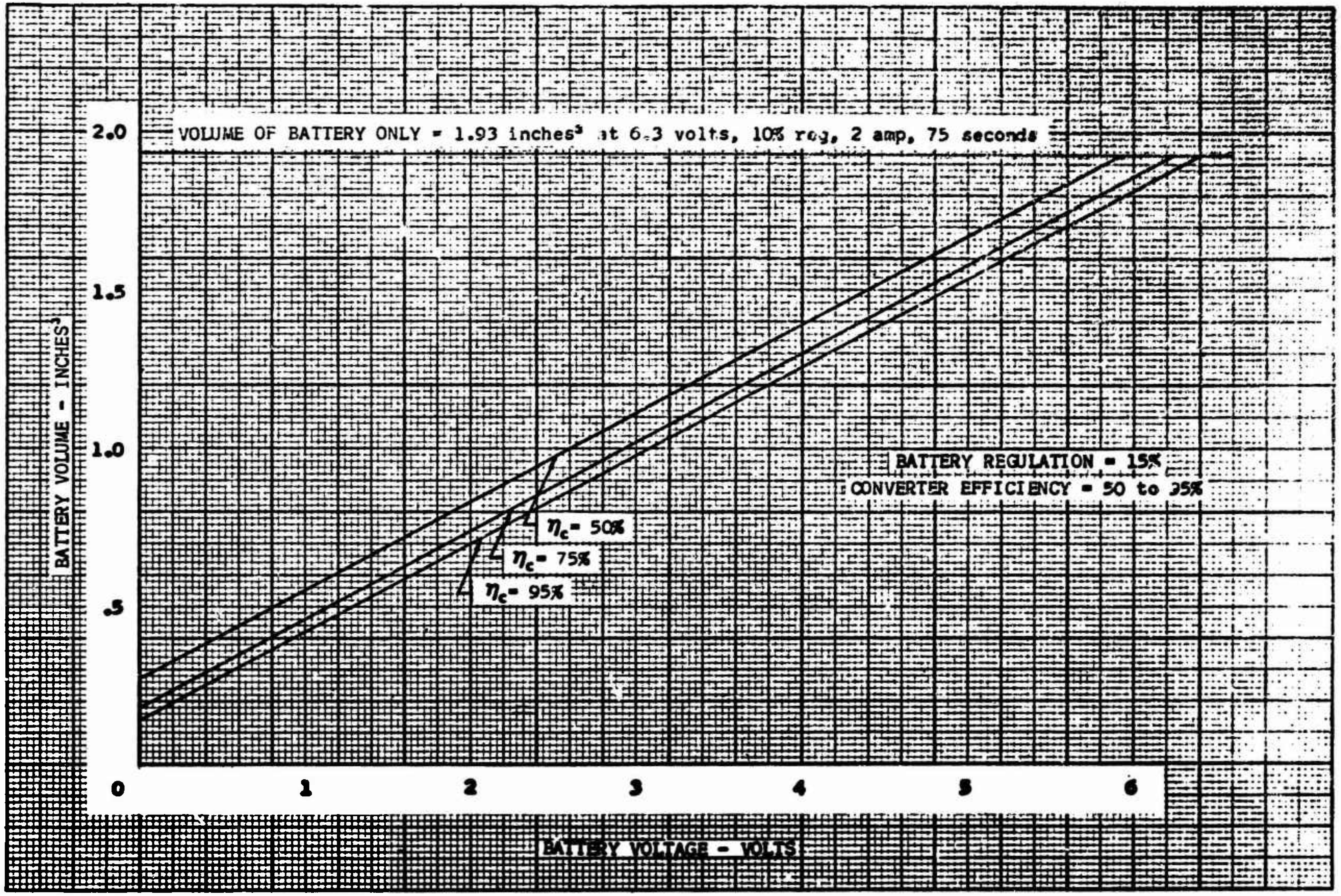


Figure 29 - BATTERY VOLUME VS BATTERY VOLTAGE (6.3-VOLT FLOATING)

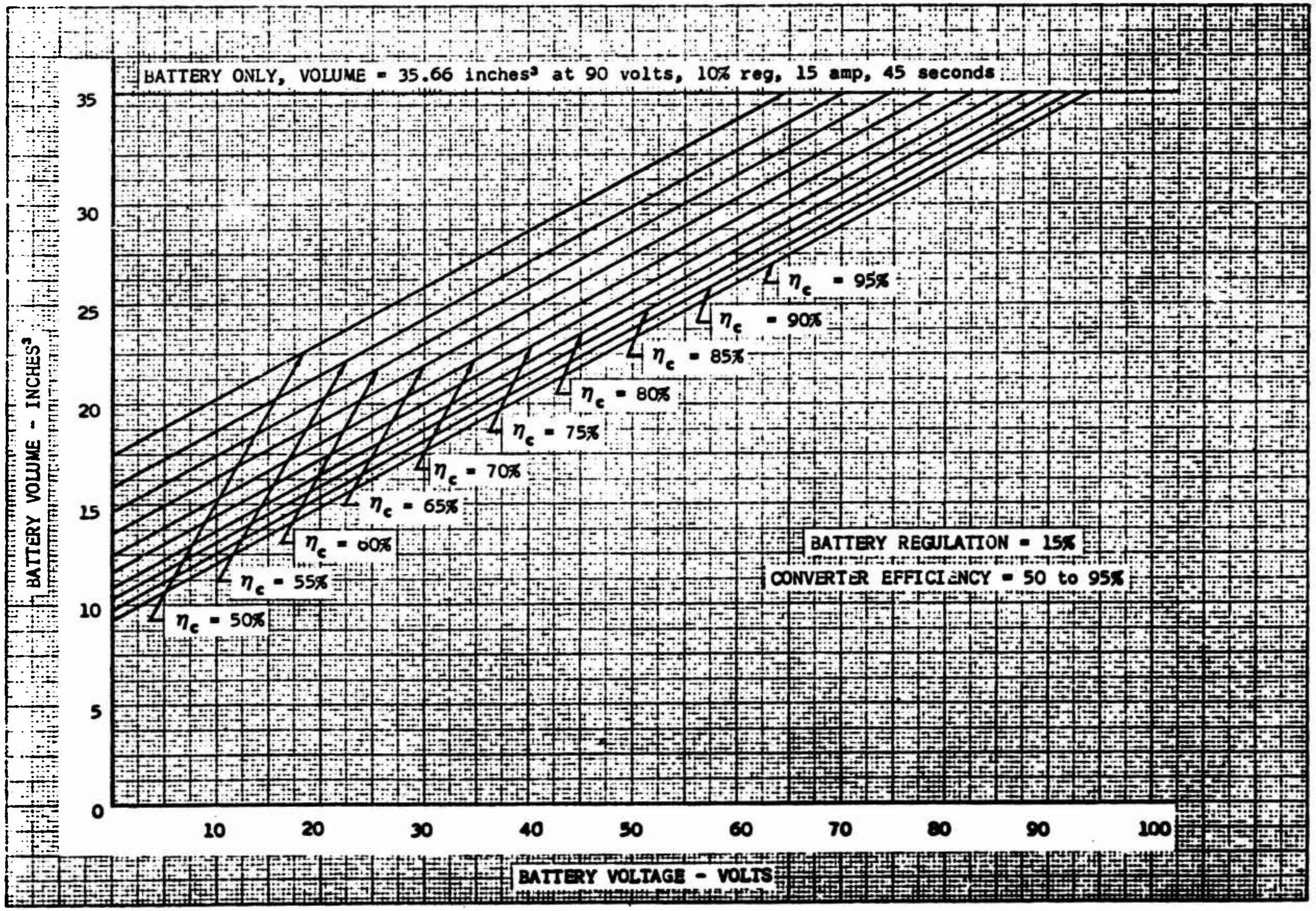


Figure 30 - BATTERY VOLUME VS BATTERY VOLTAGE (90 VOLTS)

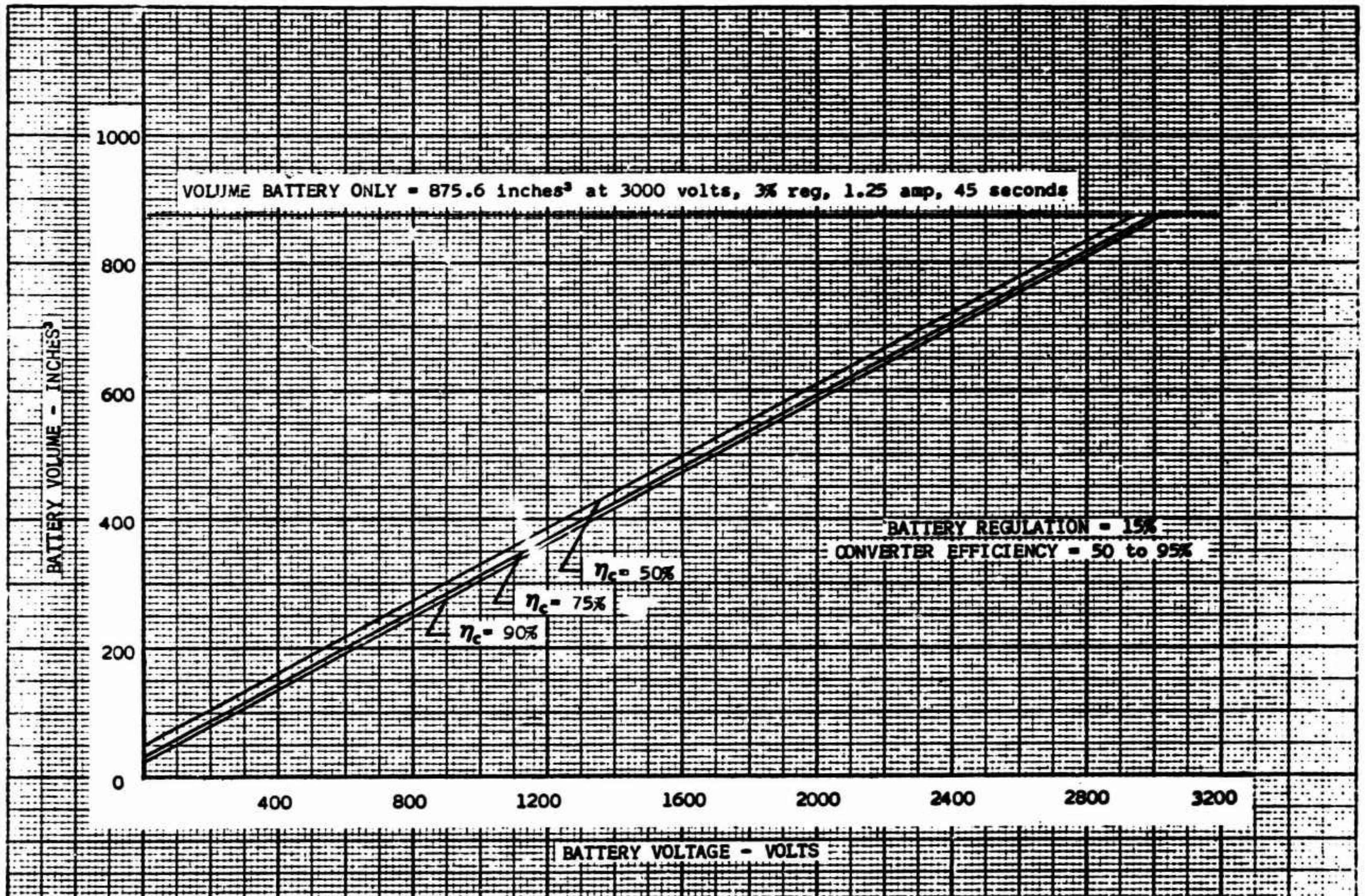


Figure 31 - BATTERY VOLUME VS BATTERY VOLTAGE (3000 VOLTS)

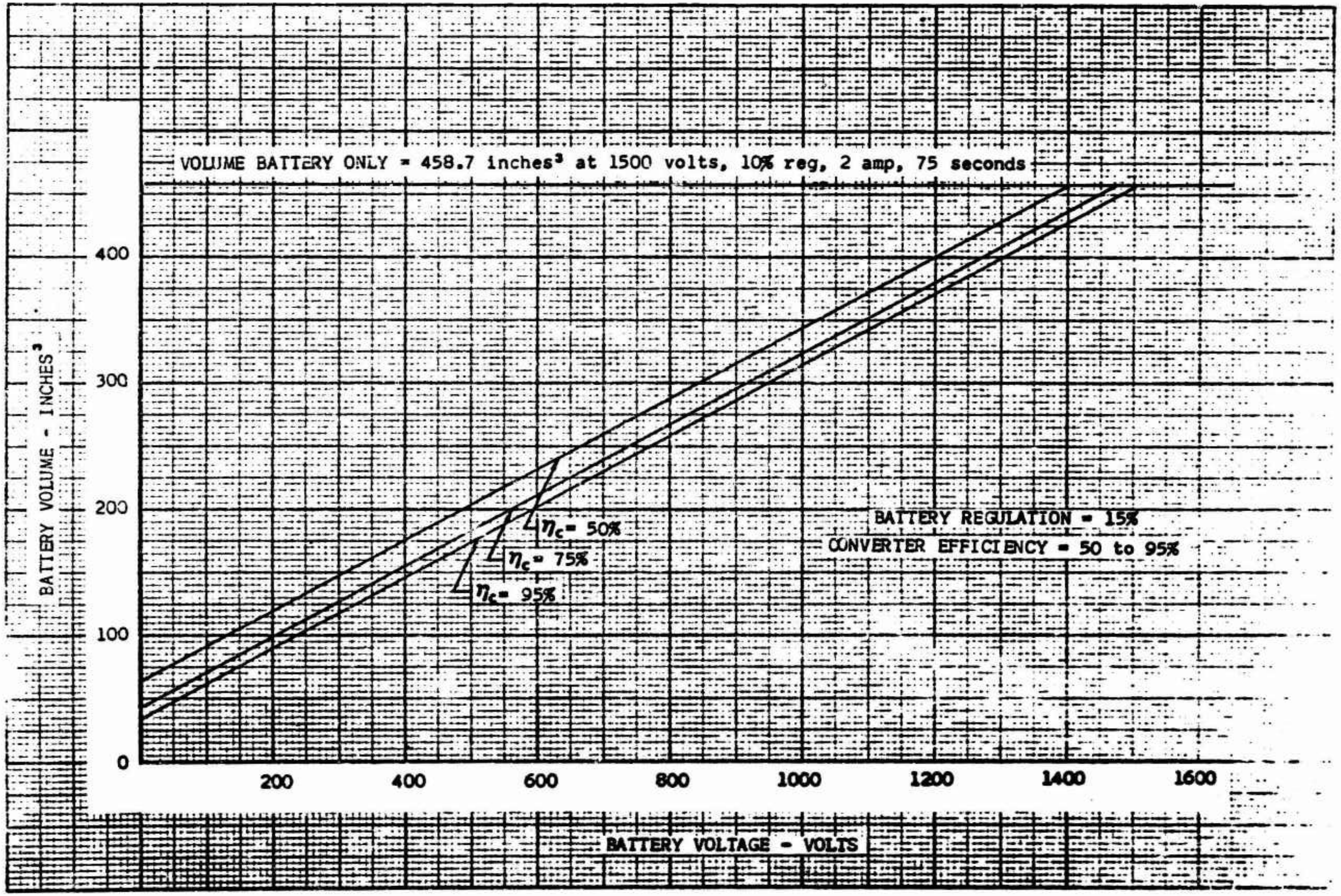


Figure 32 - BATTERY VOLUME VS BATTERY VOLTAGE (1500 VOLTS)

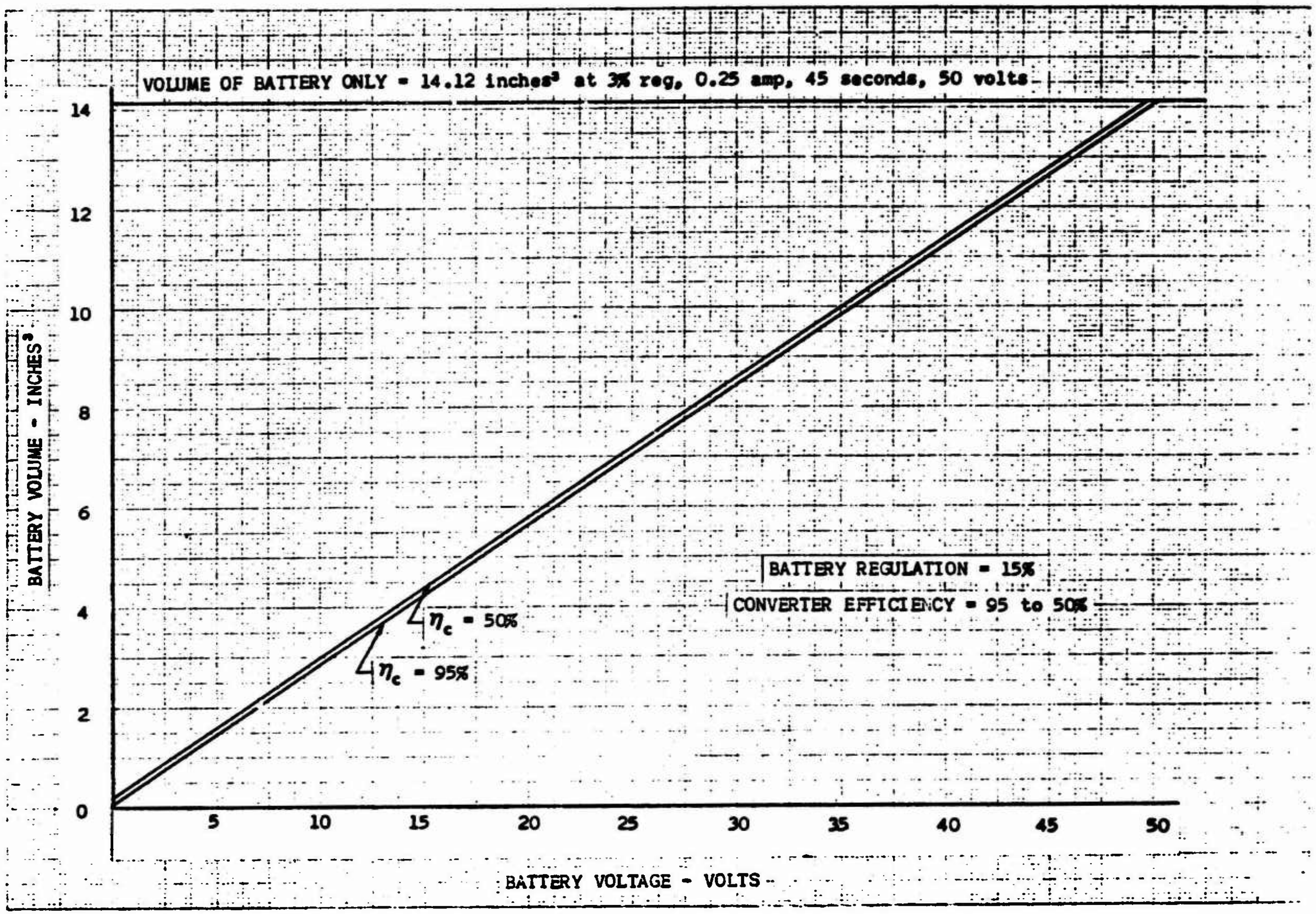


Figure 33 - BATTERY VOLUME VS BATTERY VOLTAGE (50 VOLTS)

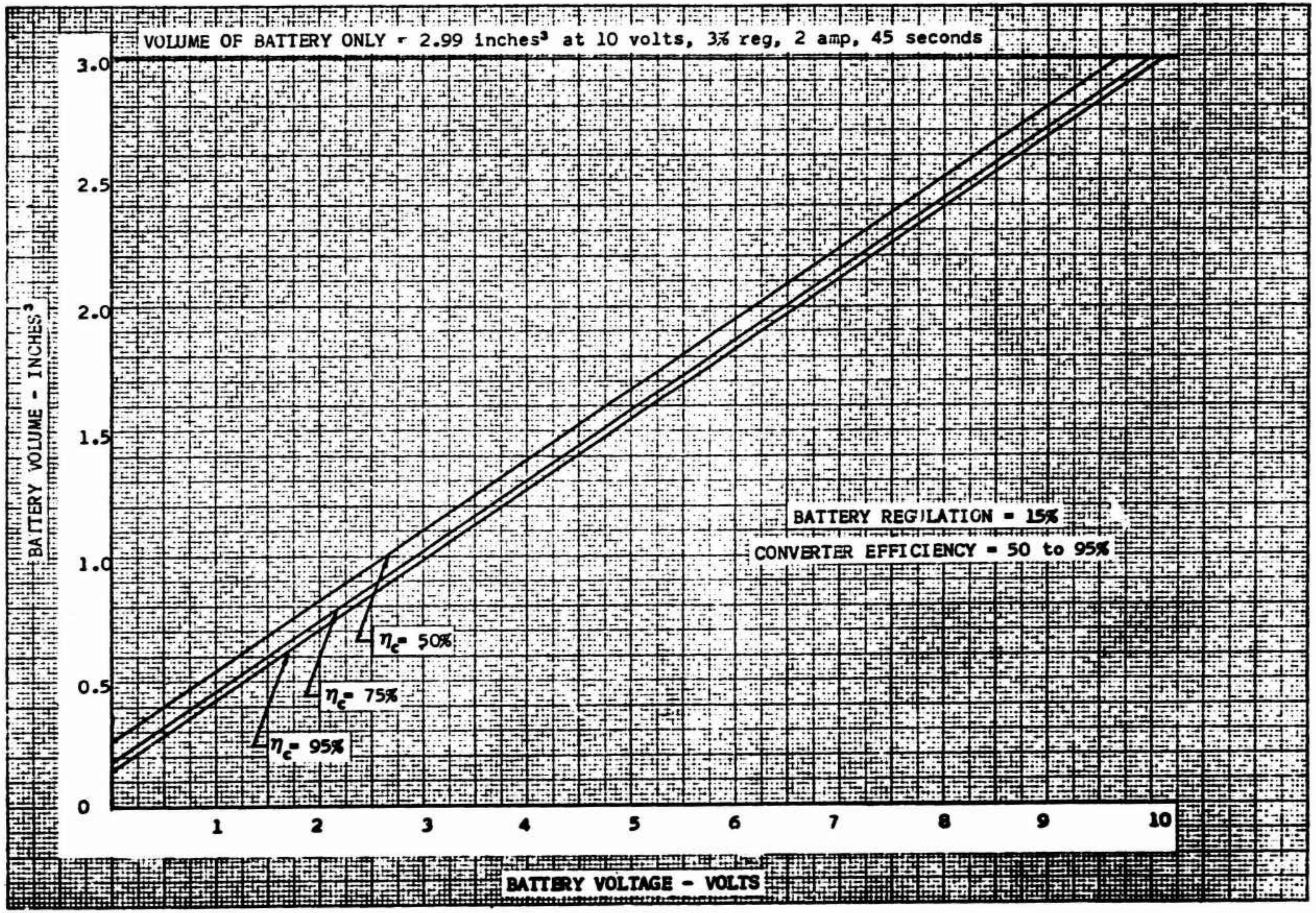


Figure 34 - BATTERY VOLUME VS BATTERY VOLTAGE (10 VOLTS)

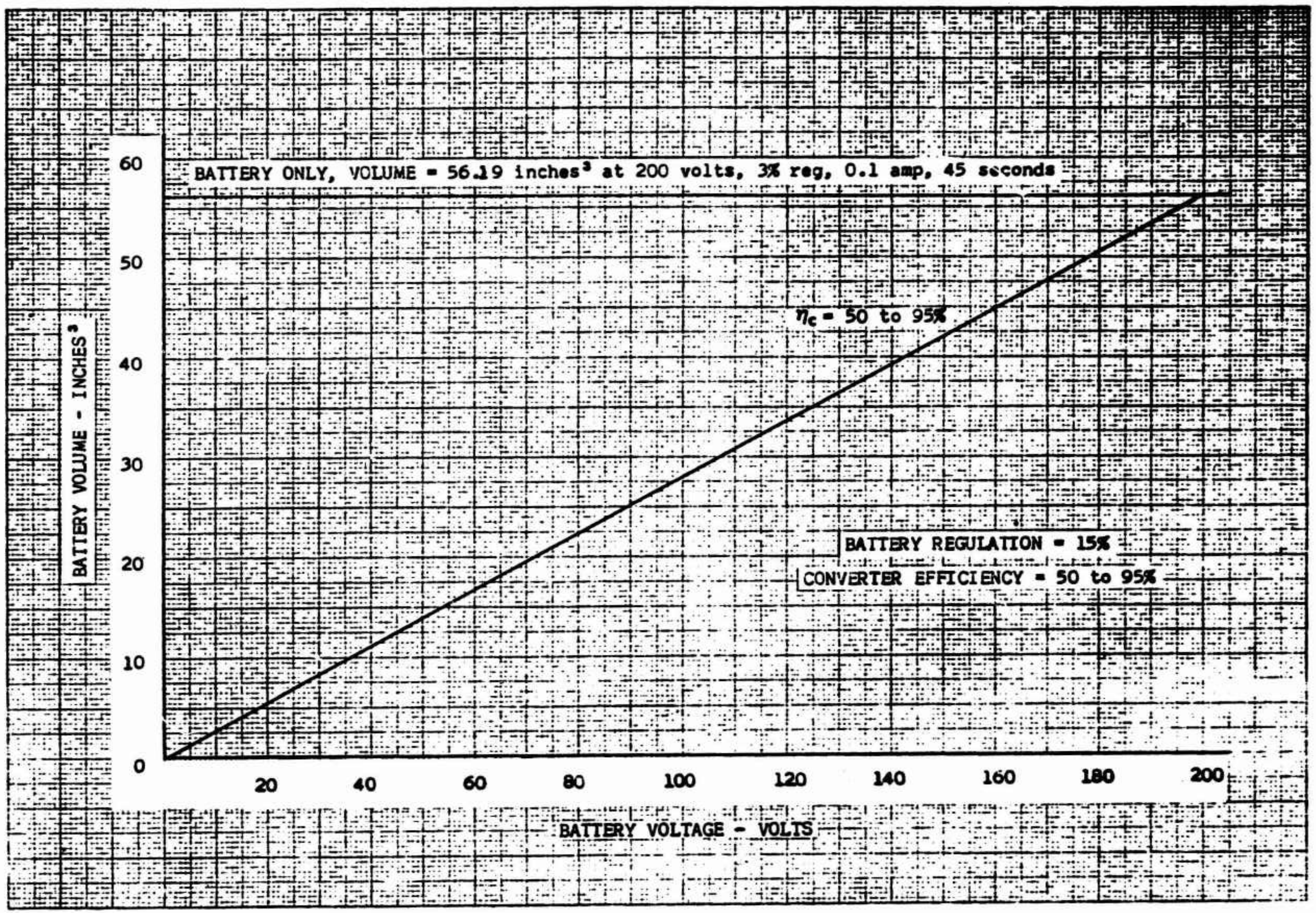


Figure 35 - BATTERY VOLUME VS BATTERY VOLTAGE (200 VOLTS)

For the remaining loads the battery voltage would be 3000 volts, with taps providing lower voltages. The battery regulation would have to be equal to the minimum requirement of all the loads. The battery energy would be the sum of all the load requirements, as shown in Table III.

TABLE III

SYSTEM ENERGY CALCULATIONS

LOAD ENERGY REQUIREMENT	BATTERY ENERGY (WATT-HOURS)
6. 3V x 9A x 75 sec/3600 sec/hr	1. 118
90V x 15A x 45 sec/3600 sec/hr	16. 880
3000V x 1. 25A x 45 sec/3600 sec/hr	46. 900
1500V x 2A x 75 sec/3600 sec/hr	62. 500
50V x 0. 25A x 45 sec/3600 sec/hr	0. 156
10V x 2A x 45 sec/3600 sec/hr	0. 250
200V x 0. 1A x 45 sec/3600 sec/hr	0. 250
TOTAL ENERGY	128. 054

The formula for determining the volume of the 3000-volt battery is:

Vol(3000-volt battery with taps for other loads) = 0. 28 + 0. 76R at ± 3% regulation

= 0. 28 x 3000 + 0. 76 x 128. 054

= 840 + 97. 25

= 937. 25 inches^3.

The total volume for two batteries supplying all the loads is 937. 25 cubic inches plus 1. 9275 cubic inches, or 939. 1775 cubic inches.

Finally, a family of curves were plotted that compared battery volume and battery terminal voltage for different values of converter efficiency in a battery-converter-regulator combination supplying all loads. The battery energy is the summation of all load requirements divided by the converter efficiency. Battery regulation is assumed to be 15%. Total load energy is 128. 054 plus 0. 2625, or 128. 3165 watt-hours. This curve is presented in Figure 36.

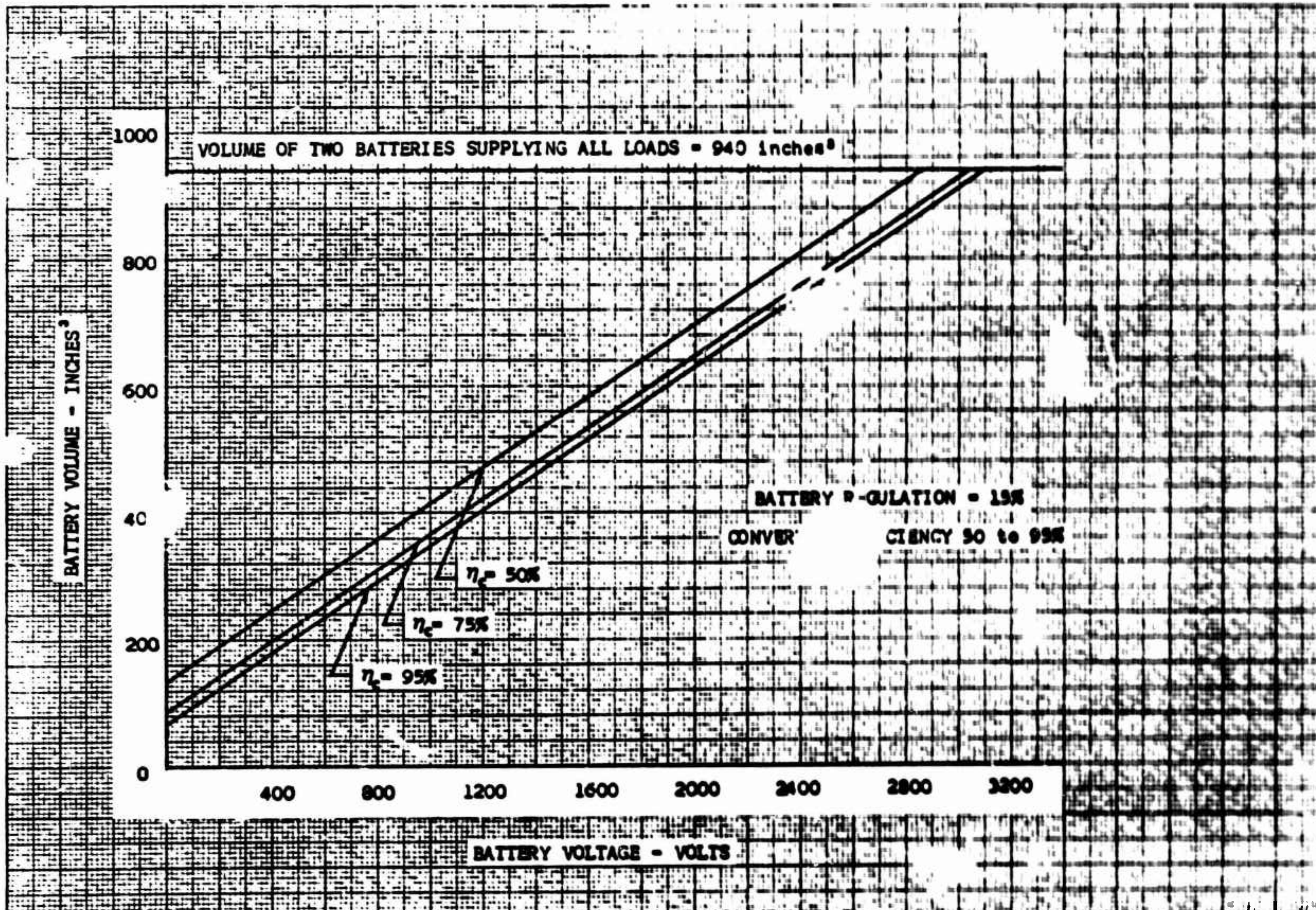


Figure 36 - BATTERY CONVERTER REGULATOR COMBINA⁻ ON SUPPLYING ALL LOADS

SECTION III

CONCLUSIONS AND RECOMMENDATIONS

1. BATTERY VOLUME AND WEIGHT

Battery volume and weight are directly proportional to battery terminal voltage and watt-hour rating, and inversely proportional to battery regulation.

In a system in which a battery supplies the load power directly, battery volume is fixed by the load voltage, energy, and regulation requirements.

In a system in which a battery supplies the load power through a converter-regulator, battery volume is not fixed by the load requirements, since a given converter-regulator would be capable of meeting a given load requirement under various conditions of battery voltage and regulation. Thus, with the converter-regulator, battery characteristics are less critical, and the battery itself might be chosen from a number of acceptable types.

2. TRANSFORMER CORES AND WINDINGS

An examination of Figures 1 and 2 shows that:

- The power dissipation in the R-03 ferrite core is less than the power dissipation in the 2-mil Orthonal for all values of f and β considered.

- The rate of decrease in power loss as core volume is increased is greater for the 2-mil Orthonal than for the R-03 ferrite. If larger core volumes had been considered, the power dissipation in the 2-mil Orthonal would have been less than the power dissipation in the R-03 ferrite.

- **For a given f β product (proportional to core volume), R-03 results in minimum power dissipation at high operating frequencies and low flux densities, while the opposite is true for the 2-mil Orthonal. This indicates that hysteresis losses are predominant in the R-03 ferrite, while eddy current losses are predominant in the 2-mil Orthonal.**

A comparative analysis of Figures 3 through 18 shows that:

- The use of R-03 ferrite as the core material would result in the least increase in system volume, for the core materials and Bt products considered. However, the loss data for the Orthonal curves should be extended to the saturation flux density of 15,000 gauss.

- As load duration increases, core loss at the point of least change in system volume decreases. Accordingly, the transformer should be designed for operation at a relatively low f β product.

- For a given operating frequency, a minimum change in system volume occurs with ferrite materials. This minimum value dictates the optimum flux density at which the core should be operated. These graphs (Figures 3 through 18) must be expanded in the areas of the minimum changes if they are to provide the most useful information.

If the operating frequency and flux density are known (from the data in Figures 3 through 6 describing the areas of minimum change for R-03 ferrite), the temperature rise in the core for any load duratio[illegible] [illegible]an be obtained from Figure 19. From Figure 6, the flux density [illegible] [illegible]ch the minimum change in system volume occurs is approximat[illegible]

at f=100 kc and 3000 gauss at f=50 kc. Examination of Figure 19 indicates that the rate of core temperature rise would be greatest for the 3000-gauss, 50-kc condition, when $\frac{\Delta T}{t}$ is 5.5 X 10^{-2} °C per second. Multiplying this factor by 75 seconds (the load duration) shows that the total temperature rise in the core is only 4.1°C.

Therefore, if R-03 ferrite cores would be used, the temperature rise in the core would be insignificant, and the effects of extreme temperatures on the core material would be a matter of little concern.

Examination of Figures 20 through 23 shows that, as expected, the winding factor, K, should be made as large as possible. In addition, the curves in these figures show that:

- The optimum current density decreases as the winding factor increases.

- The optimum current density decreases if either the battery constant, B, or the load duration, t, is increased.

- The battery constant, B, has only a minor effect on the optimum current density.

Figures 24 and 25 show that temperature rises in the winding as a function of current density. On the basis of optimum current densities of 800 at K = .7 and 1300 at K = .1 for the 15-second load duration, and 610 at K = .7 and 960 at K = .1 for the 75-second duration, the following conclusions can be made:

- **The temperature rise in a winding supplying a 45-second load will be from 70°C to 300°C, depending on the winding factor.**

- **The temperature rise in a winding supplying a 75-second load will be from 110°C to 300°C, depending on the winding factor.**

- **Since the winding temperature rise and the transformer volume are dependent on achieving the maximum winding factor, additional effort should be expended in examining various wire types to determine an optimum wire and insulation material.**

3. TRANSISTORS

Regarding a suitable transistor for the missile power supply, the following conclusions and recommendations are made:

In general:

- A specific transistor for use in all the system configurations studied is not presently available, and therefore cannot be recommended.

- Equations have been developed that show the relationship of transistor losses and battery volume for any combination of transistor(s) and battery. These equations can be used to specify the minimum achievable system volume for a specific combination of transistor(s) and battery.

- Generalized equations have been developed that show the relationship between transistor efficiency, system power level, and system power transfer duration. With these equations, the specific transistor(s) required for an optimized system can be determined for any combinations of transistors, system power levels, and system

transfer durations. These equations will specify the minimum system volume (and thus the minimum transistor volume) for a specific mission, consistent with overall system efficiency.

Specifically:

- Battery volume (and thus system volume) are directly proportional to transistor losses. The equations developed will enable the selection of transistors that will minimize increases in battery volume due to transistor losses.

- The operating frequency of the transistor selected for use in a specific system must be compatible with the results obtained from the transformer power loss analysis for the same system.

- Total transistor switching losses are directly proportional to the operating frequency of the converter oscillator.

- On the basis of the studies thus far conducted, the Delco Radio '2581 transistor appears to be suitable for use in an 8.2-kw converter for the missile powe supply.

4. SYSTEM VOL ME

The system volume investigations to date have resulted in the following conclusions and recommendations.

- The total battery volume for individual batteries supplying each load independently would be 1447 cubic inches.

- The total volume of the battery supplying the 6.3-volt, floating load and one other battery supplying the remaining loads would be 939 cubic inches.

- The total energy required to satisfy all loads would be 128 watt-hours.

- In a battery and converter-regulator combination, where minimum battery volume is desired, the converter power transformer should provide for the maximum possible step-up of battery voltage. Accordingly, battery voltage should be as low as possible, without entering the region in which converter efficiency is drastically reduced, and in which the converter volume is drastically increased as the converter input voltage is decreased.

- Of the systems investigated to date, the single battery and converter-regulator combination holds the most promise for minimizing the battery volume.

APPENDIX A

BATTERY WEIGHT AND VOLUME CALCULATIONS

APPENDIX A

BATTERY WEIGHT AND VOLUME CALCULATIONS

1. BATTERY VOLUME

Using data received from the Yardney Electric Corporation, plots were developed that compared battery volume against nominal terminal voltage for various fixed values of battery regulation in percent and battery energy in watt-hours. These curves shown in Figure A-1, indicated that battery volume is a function of battery terminal voltage, energy, and regulation. Therefore, volume may be expressed as:

$$\text{Vol} = AV + B_1R \text{ at } 5\% \text{ regulation}$$

$$\text{Vol} = AV + B_2R \text{ at } 10\% \text{ regulation}$$

$$\text{Vol} = AV + B_3R \text{ at } 15\% \text{ regulation}$$

Where:

A = a constant with dimensions of $\text{in.}^3/\text{volt}$

B = a constant with dimensions of $\text{in.}^3/\text{watt-hour}$

Figure A-1 indicates that the average value of A is 0. 28 cubic inch per volt. Therefore, the general equation for battery volume becomes:

$$\text{Vol} = 0.28\,V + BR$$

The curves shown in Figure A-2 were plotted to find B for the three fixed values of battery regulation, which are:

B_1 = 0.72 at 5% regulation

B_2 = 0.62 at 10% regulation

B_3 = 0.53 at 15% regulation

The equations for battery volume at different values of regulation are:

Vol = 0.28 V + 0.72 R at 5% regulation

Vol = 0.28 V + 0.62 R at 10% regulation

Vol = 0.28 V + 0.53 R at 15% regulation

To generalize the volume equation, it was assumed that a linear relationship exists between the values of B found for the different values of regulation. On that basis, a general expression for B can be written as follows:

B = X regulation + Y

From this equation, two simultaneous equations can be written for B at different values of regulation, as follows:

0.72 = X5 + Y at 5% regulation (1)

0.62 = X10 + Y at 10% regulation (2)

Subtracting equation (2) from equation (1) yields:

$$0.1 = -5X$$

$$X = \frac{-0.1}{5}$$

$$X = -0.02$$

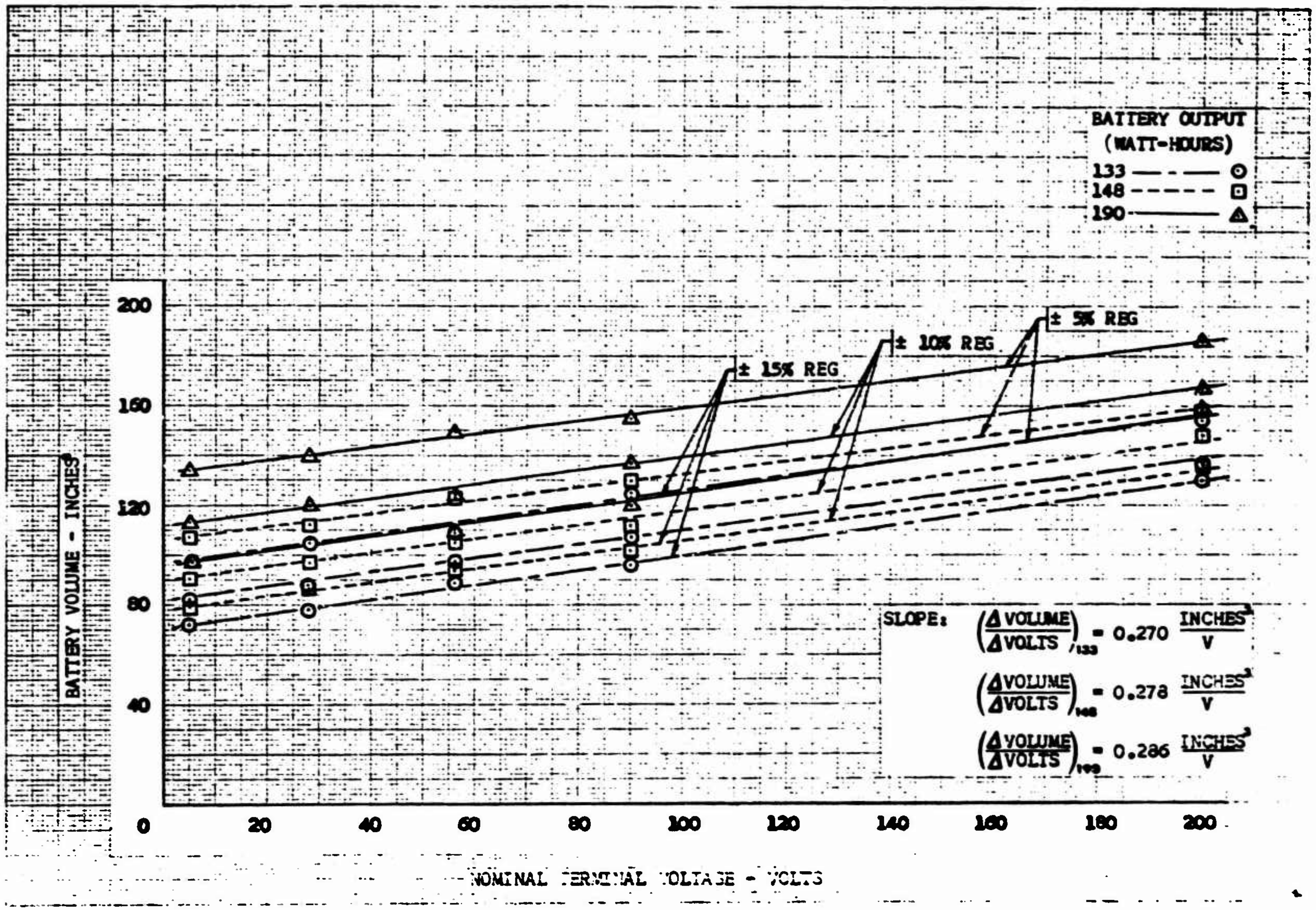


Figure A-1 - BATTERY VOLUME VS NOMINAL BATTERY TERMINAL VOLTAGE FOR FIXED VALUES OF BATTERY ENERGY AND REGULATION (CASE 1)

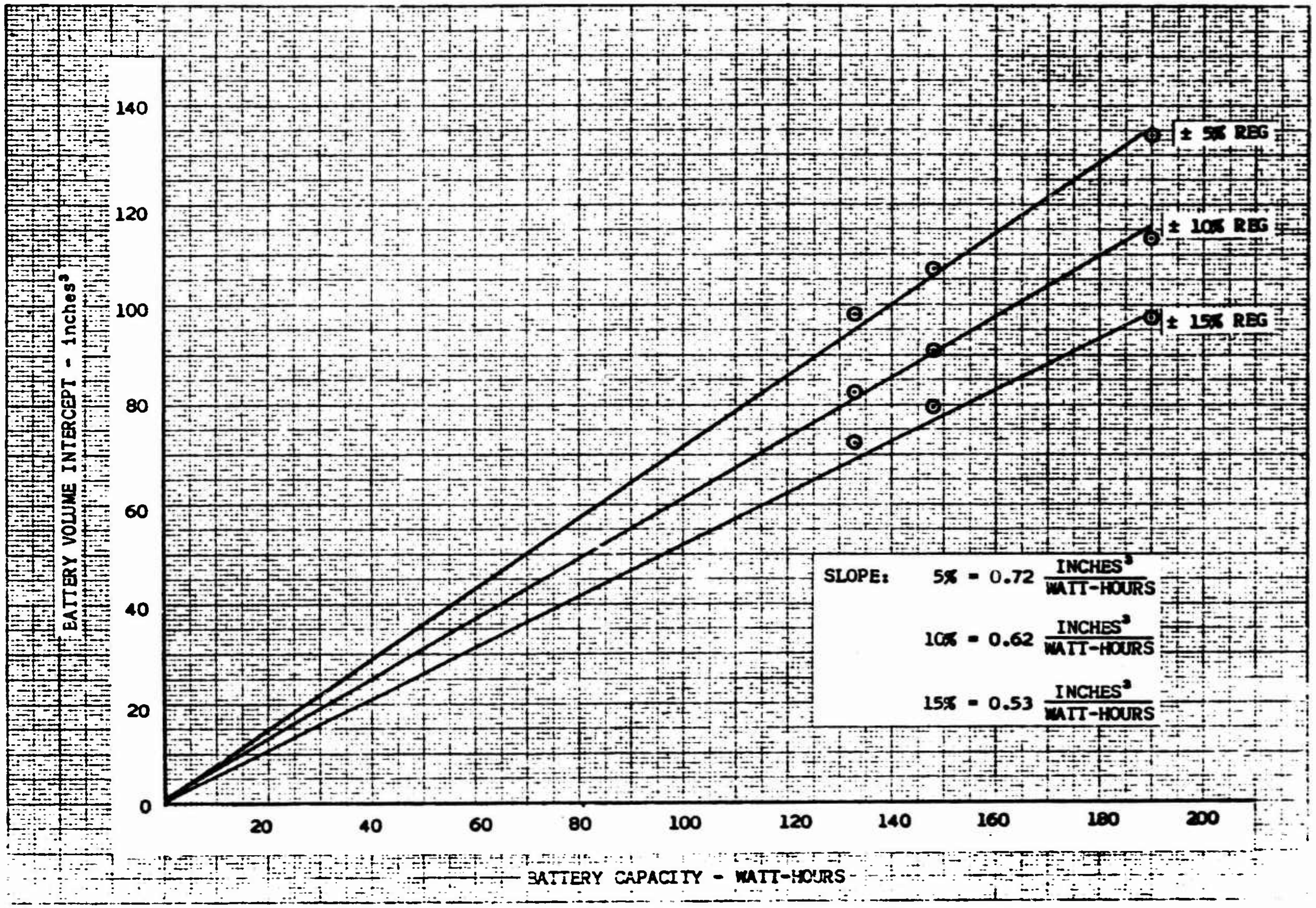


Figure A-2 - BATTERY VOLUME VS BATTERY ENERGY FOR FIXED VALUES OF BATTERY REGULATION (CASE 2)

Substituting X into equation (1):

$$0.72 = (-0.02)(5) + Y$$

$$Y = 0.72 + 0.1$$

$$Y = 0.82$$

The general equation for battery volume is:

$$Vol = 0.28V + (-0.02\ REG + 0.82)\ R$$

where: Vol = Volume of battery in cubic inches
V = Nominal battery terminal voltage in volts
R = Battery energy in watt-hours
REG= Battery voltage regulation in percent

2. BATTERY WEIGHT

The method used for deriving the equations for battery weight is the same as that for volume. The curves in Figure A-3 and A-4 were plotted from data received from the Yardney Electric Corporation.

The weight equations are:

$$Weight = AV + B_1R \text{ at } 5\% \text{ regulation}$$

$$Weight = AV + B_2R \text{ at } 10\% \text{ regulation}$$

$$Weight = AV + B_3R \text{ at } 15\% \text{ regulation}$$

where: A = A constant with dimensions of lb/volt
B = A constant with dimensions of lb/watt-hour

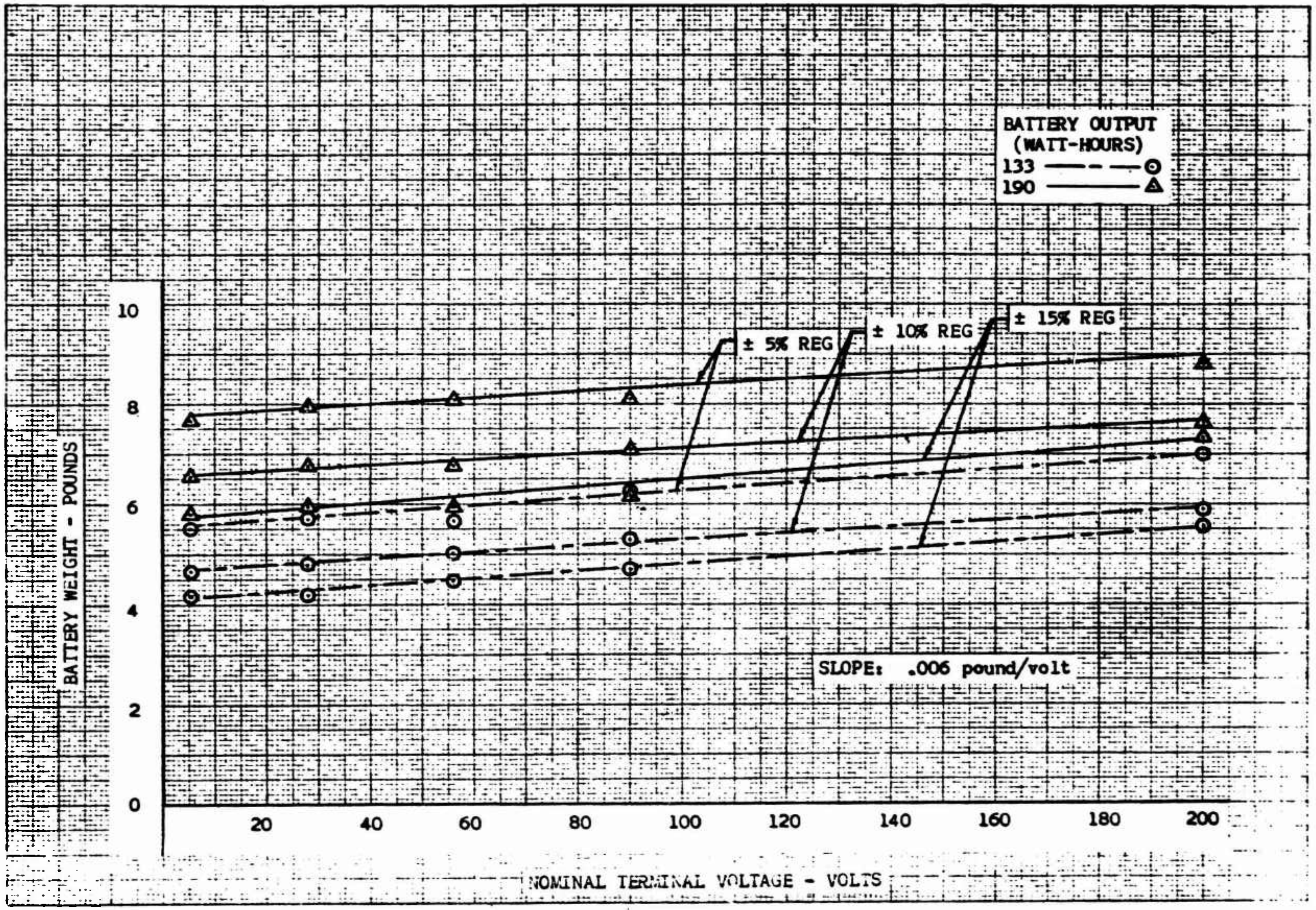


Figure A-3 - BATTERY WEIGHT VS NOMINAL BATTERY TERMINAL VOLTAGE FOR FIXED VALUES OF BATTERY ENERGY AND REGULATION (CASE 3)

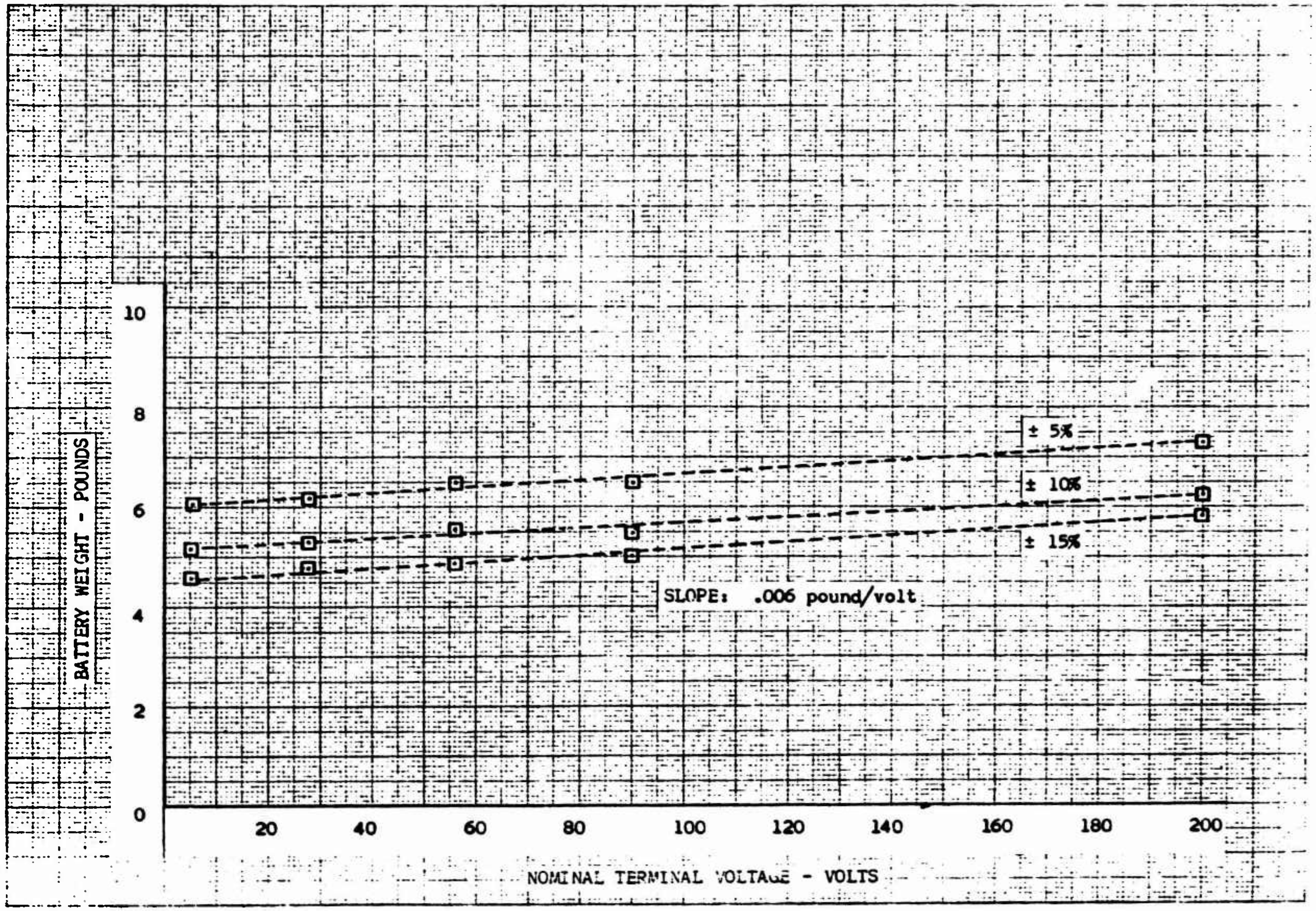


Figure A-4 - BATTERY WEIGHT VS NOMINAL BATTERY TERMINAL VOLTAGE FOR FIXED VALUES OF BATTERY ENERGY AND REGULATION (CASE 4)

Figures A-3 and A-4 indicate that A is 0.006 pound per volt. Therefore, the general equation for battery weight is:

$$\text{Weight} = 0.006V + BR$$

The curves in Figure A-5 were plotted to find B for the three fixed values of battery regulation, which are:

$B_1 = 0.042$ at 5% regulation

$B_2 = 0.035$ at 10% regulation

$B_3 = 0.0295$ at 15% regulation

The equations for battery weight at different values of regulation are:

Weight $= 0.006V + 0.042\,R$ at 5% regulation

Weight $= 0.006V + 0.035\,R$ at 10% regulation

Weight $= 0.006V + 0.0295R$ at 15% regulation

where: weight = Weight of battery in pounds

V = Nominal battery terminal voltage in volts

R = Battery energy in watt-hours.

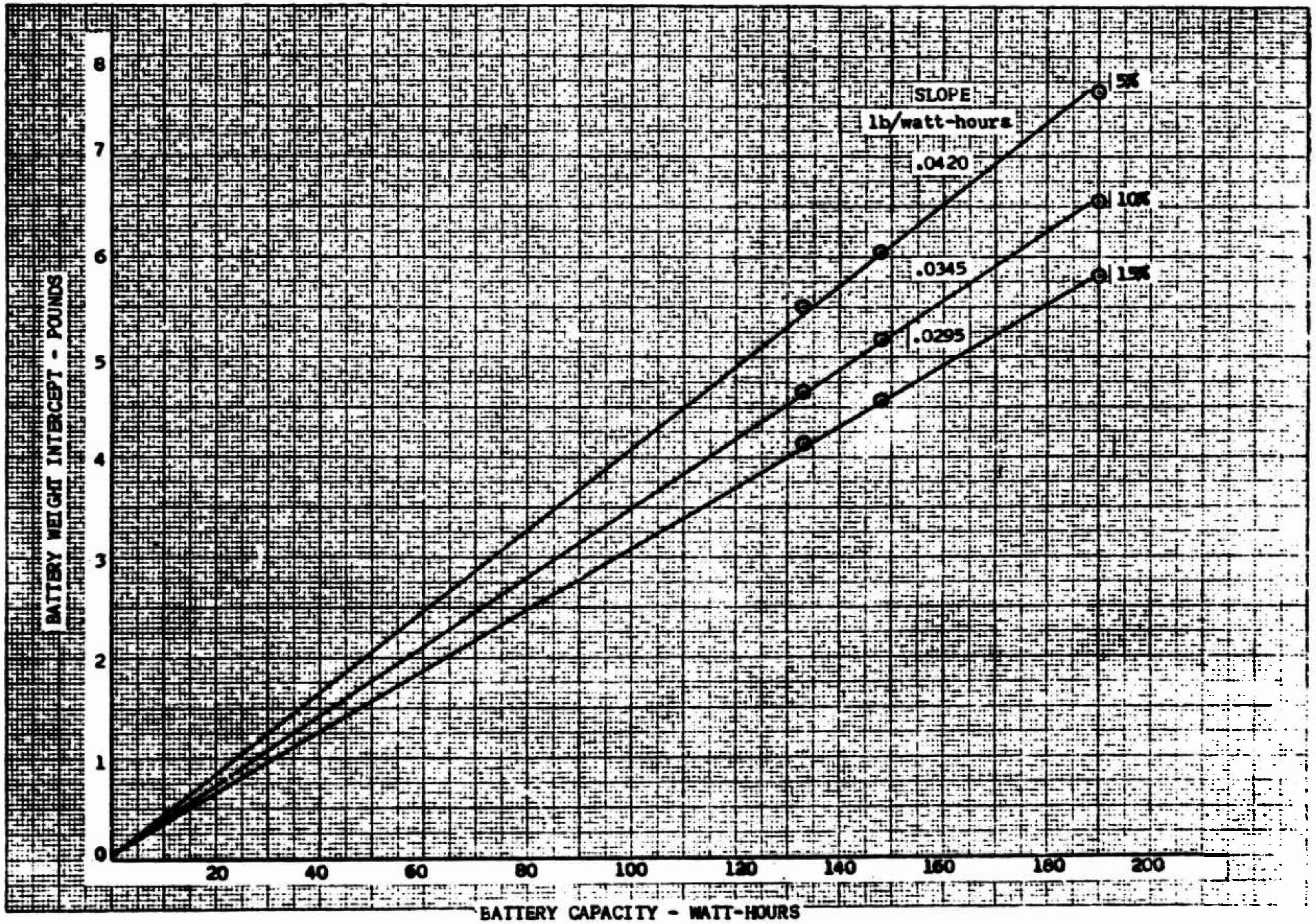


Figure A-5 - BATTERY WEIGHT VS BATTERY ENERGY FOR FIXED VALUES OF BATTERY REGULATION

APPENDIX B

CONVERTER TRANSFORMER VOLUME ANALYSIS

APPENDIX B

CONVERTER TRANSFORMER VOLUME ANALYSIS

1 GENERAL

Considering only the battery and converter transformer in the system, the volume of these components is:

$$V_T = V_B + V_{TR}$$

where V_T = Total volume

V_B = Battery volume

V_{TR} = Transformer volume.

Previously however, V_B was established as follows:

$$V_B = AV + BR.$$

where V = Battery terminal voltage

R = Battery rating in watt-hours

A = Constant with dimensions of $\frac{in^3}{Volt}$

B = Constant (dependent on battery regulation) with dimensions of $\frac{in^3}{watt\text{-}hour}$

The required battery rating (R) is dependent on the load requirements and the power loss of the transformer.

$$R = (E_L I_L t + P_{TR} t) \frac{1}{3600}$$

R = Battery rating, in watt-hours

E_L = Load voltage, in volts

I_L = Load current, in amperes

t = Load duration, in seconds

P_{TR} = Power dissipated in the transformer, in watts

$$\therefore V_T = AV + \frac{B}{3600} (E_L T_L t + P_{TR} t) + V_{TR}$$

$$V_T = AV + \frac{BE_L I_L t}{3600} + \frac{BP_{TR} t}{3600} + V_{TR}$$

$$P_{TR} = P_C + P_W$$

where P_C = Power dissipated in the core, in watts

P_W = Power dissipated in the winding, in watts

$$V_{TR} = V_C + V_{wg}$$

where V_C = Total core volume, in cu. in.

V_{wg} = Total winding volume, in cu. in.

$$V_T = AV + \frac{BE_L I_L t}{3600} + \frac{B t (P_C + P_W)}{3600} + V_C + V_{wg}$$

$$V_T = \left[AV + \frac{BE_L I_L t}{3600}\right] + \left[\frac{B_t P_C}{3600} + V_C\right] + \left[\frac{B_t P_W}{3600} + V_{wg}\right]$$

or

$$V_T = V_L + \Delta V_1 + \Delta V_2$$

The terms in the first bracket of the equation define the battery volume required to supply the load requirements, the terms in the second bracket define the increase in system volume caused by adding a transformer core, and those in the third bracket define the increase in system volume caused by adding a transformer winding. Each bracketed term of this equation can be investigated separately, and minimum points can be determined if they exist.

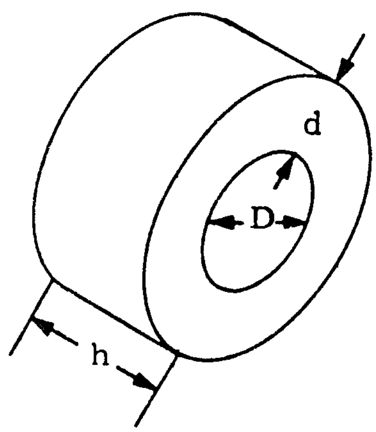
2. STUDY OF EFFECTS ON TOTAL SYSTEM VOLUME DUE TO ADDING A TRANSFORMER CORE

$$\Delta V_1 = \frac{B^t P_C}{3600} + V_C \qquad (1)$$

The core parameters P_C and V_C must be expressed in terms of circuit parameters. Since the total power dissipated in the core material (P_C) is dependent on the core volume (V_C), the core volume will be developed first.

a. Derivation of V_C as a Function of Circuit Parameters

Assume a toroidal core with dimensions as shown below:



Then:

Window Area $= A_W = \pi/4\ D^2$

Core Area $= A_C = dh$

$$V_W = \pi/4\ D^2\ h$$

$$V_W + V_C = \pi/4\ (D + 2d)^2\ h$$

$$V_C = \pi/4\ (D + 2d)^2\ h - \pi/4\ D^2 h$$

$$= \pi/4\ (D^2 + 4\ Dd + 4d^2)\ h = \pi/4\ D^2 h$$

$$= \pi/4\ D^2 h + \pi\ Dd\ h + \pi\ d^2 h - \pi/4\ D^2 h$$

$$= \pi\ dh\ (D + d)$$

Assuming a given form factor for the core for minimum transformer weight (as specified in AD 433 159, Voltage Regulation and Conversion in Unconventional Electricity Generator Systems),

$$d = \frac{1}{\sqrt{2}}\ D \qquad h = \sqrt{2}\ D$$

$$A_C = \frac{1}{\sqrt{2}}\ D \times \sqrt{2}\ D = D^2$$

$$A_W = \pi/4\ D^2$$

$$A_C A_W = \pi/4\ D^4$$

$$D = \sqrt[4]{\frac{4}{\pi}\ A_C\ A_W}$$

$$V_C = \pi \frac{1}{\sqrt{2}}\ D\sqrt{2}\ D\ (D + \frac{1}{\sqrt{2}}\ D) = \pi\ D^3 \left(\frac{\sqrt{2} + 1}{\sqrt{2}}\right)$$

$$V_C = \frac{\sqrt{2} + 1}{\sqrt{2}}\ \pi\ (\frac{4}{\pi})^{3/4}\ (A_C\ A_W)^{3/4}$$

$$V_C = \frac{\sqrt{2} + 1}{\sqrt{2}}\ 2\sqrt{2}\ \frac{\pi^{1/4}}{\pi^{3/4}}\ (A_C\ A_W)^{3/4}$$

$$V_C = (2\sqrt{2} + 2)\ \pi^{1/4}\ (A_C A_W)^{3/4}$$

$$V_C = 6.35\ (A_C\ A_W)^{3/4} \qquad (2)$$

Assuming a bifilar-wound transformer, $A_C A_W$ can be expressed in terms of the circuit requirements as follows:

$$\frac{N_P}{2} A_C = \frac{E_P \times 10^8}{4 f \beta S}$$

N_P = Total number of turns on the primary winding

E_P = Voltage applied to the primary, in volts

f = Operating frequency, in cycles per second

β = Flux density in the core material, in lines per sq. in.

S = Core stacking factor

If K, the winding factor, is defined as the ratio of the copper area, A_{CU}, within the core window to the area of the core window, then:

$$K = \frac{A_{CU}}{A_W}$$

$$A_{CU} = N_P W_{AP} + N_S W_{AS}$$

N_S = Total number of turns on the secondary

W_{AP} = Conductor area per primary turn, in sq. in.

W_{AS} = Conductor area per secondary turn, in sq. in.

Assuming $$N_P W_{AP} = N_S W_{AS}$$

$$A_{CU} = 2 N_P W_{AP}$$

Further, if J, current density, is defined as follows:

$$J = \frac{\text{Total primary current through } A_W}{\text{Total } A_{CU} \text{ of primary winding in the window}}$$

Then:

$$J = \frac{N_P/2\ I_P}{A_{CU}}$$

$$A_{CU} = \frac{N_P I_P}{2J}$$

$$\frac{A_W}{N_P} = \frac{I_P}{2KJ}$$

$$\frac{N_P}{2} A_C \times \frac{A_W}{N_P} = \frac{E_P \times 10^8}{4 f B S} \times \frac{I_P}{2 K J}$$

$$A_C A_W = \frac{E_P I_P \times 10^8}{4 f B S K J} = \frac{P \times 10^8}{4 f B S K J}$$

Substituting into equation (2):

$$V_C = \frac{6.35 \times 10^6}{2.835} \left(\frac{P \times 10^8}{4 f B S K J} \right)^{3/4}$$

$$V_C = 2.24 \times 10^{6} \left(\frac{P}{f\,\delta\,S\,K\,J} \right)^{3/4}$$

$$V_C = \left(\frac{2.94 \times 10^{8}\,P}{f\,\delta\,S\,K\,J} \right)^{3/4} \qquad (3)$$

b. <u>Derivation of P_C as a Function of Circuit Parameters</u>

Core loss data are presented on the data sheets in terms of $\frac{\mu \text{ watts}}{\text{cm}^3 \text{ cps}}$ for ferrites or in terms of $\frac{\text{watts}}{\text{pound}}$ for tape-wound cores.

Let C_{L1} = core loss factor $\frac{\mu \text{ watts}}{\text{cm}^3 \text{ cps}}$

C_{L2} = core loss factor $\frac{\text{watts}}{\text{pound}}$

$$P_C = C_{L1} \times \frac{1}{6.1 \times 10^{-2}} \times V_C \times f \times 10^{6}$$

$$\text{watts} = \frac{\mu \text{ watts}}{\text{cm}^3 \text{ cps}} \times \frac{\text{cm}^3}{\text{in.}^3} \times \frac{\text{watts}}{\mu \text{ watt}} \times \text{in.}^3 \times \text{cps}$$

$$P_C = 1.64 \times 10^{-5}\, C_{L1} \times V_C \times f \qquad (4)$$

or

$$P_C = C_{L2} \times \delta \,\frac{\text{lb}}{\text{in.}^3} \times V_C \text{ in.}^3$$

δ = density of the core in $\frac{\text{lb}}{\text{in.}^3}$

$$P_C = 2.24 \times 10^{+6}\, \delta\, C_{L2} \left(\frac{P}{f\,\delta\,S\,K\,J} \right)^{3/4}$$

c. **System Volume Analysis**

$$\Delta V_1 = \frac{Bt\,P_C}{3600} + V_C$$

substituting for P_C from equation (4)

$$\Delta V_1 = Bt\;4.55 \times 10^{-9}\, f\, C_{L1}\, V_C + V_C$$

substituting for V_C from equation (3) and transposing K, J, and P in the equation:

$$\left(\frac{K\,J}{P}\right)^{3/4} \Delta V_1 = 4.55 \times 10^{-9}\, Btf\, C_{L1} \left(\frac{2.94 \times 10^8}{f\,\delta\,S}\right)^{3/4} + \left(\frac{2.94 \times 10^8}{f\,\delta\,S}\right)^{3/4} \qquad (5)$$

d. **Derivation of Expression for Core Temperature Rise**

The specific heat, C_S, for most core materials is given in units of $\frac{\text{calories}}{\text{gm}\,^\circ\text{C}}$. The density, δ, is given in units of $\frac{\text{gm}}{\text{cm}^3}$.

In order to obtain the specific heat, C_S', in terms of the desired units of $\frac{\text{watt-hours}}{\text{in.}^3\,^\circ\text{C}}$, the following conversion is performed.

$$C_S' = C_S \times \delta \times \frac{\text{cm}^3}{\text{in.}^3} \times \frac{\text{watt-hours}}{\text{calories}}$$

$$= \frac{\text{calories}}{\text{gm}\,^\circ\text{C}} \times \frac{\text{gm}}{\text{cm}^3} \times \frac{\text{cm}^3}{\text{in.}^3} \times \frac{\text{watt-hours}}{\text{calories}} = \frac{\text{watt-hours}}{\text{in.}^3\,^\circ\text{C}}$$

$$\frac{\text{cm}^3}{\text{in.}^3} = 16.4$$

$$\frac{\text{watt-hours}}{\text{calories}} = 1.16 \times 10^{-3}$$

$$C_S' = 19.05 \times 10^{-3}\, C_S\, \delta \qquad (6)$$

Assuming no energy loss through convection, conduction, or radiation:

$$\text{Core temperature rise} = \Delta T = P_C t \frac{1}{3600} \times \frac{1}{V_C} \times \frac{1}{C_S'} = \frac{P_C\, t}{3600\, V_C C_S'}$$

substituting for P_C from equation (4)

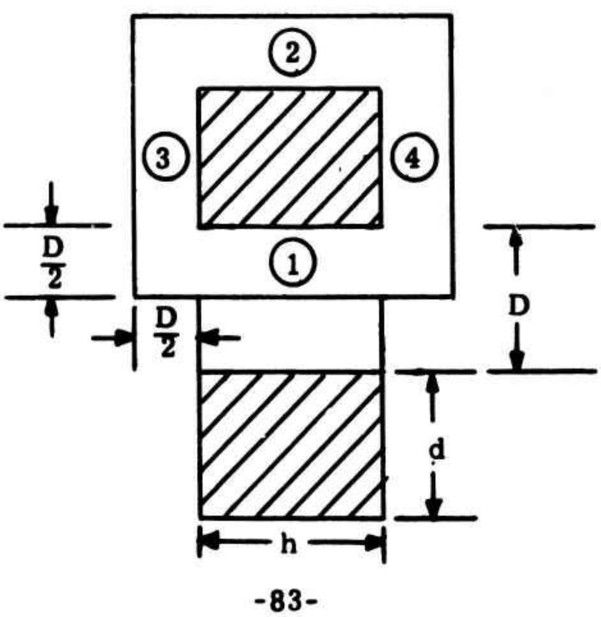
$$\Delta T = \frac{1.64 \times 10^{-5}\, C_{L1}\, f\, V_C\, t}{3600\ C_S'}$$

$$\frac{\Delta T}{t} = \frac{1}{C_S'}\ (4.55 \times 10^{-9}\, f\, C_{L1}) \qquad (7)$$

3. STUDY OF EFFECTS ON TOTAL SYSTEM VOLUME DUE TO ADDING A TRANSFORMER WINDING

$$\Delta V_2 = \frac{Bt\, P_W}{3600} + V_{wg}$$

Assume that the winding is of the form shown in the cross section below.



Volume of sections 1 and 2 $= A_W (h + D)$

Volume of sections 3 and 4 $= A_W d$

$$V_{wg} = 2 \left[A_W (h + D) + A_W d \right]$$

$$V_{wg} = 2 \ A_W (h + d + D)$$

From previous calculations:

$$A_W = \pi/4 \ D^2$$

$$h = \sqrt{2} \ D$$

$$d = \frac{1}{\sqrt{2}} \ D$$

$$A_C A_W = \pi/4 \ D^4, \text{ or } D = \sqrt[4]{\frac{4 \ A_C \ A_W}{\pi}}$$

$$V_{wg} = 2A_W (h + d + D)$$

$$= \pi/2 \ D^2 \left(\sqrt{2} \ D + \frac{1}{\sqrt{2}} \ D + D\right)$$

$$= \left(\sqrt{2} + \frac{1}{\sqrt{2}} + 1\right) \pi/2 \ D^3$$

$$= (3.121) \ \pi/2 \left(\frac{4A_C A_W}{\pi}\right)^{3/4}$$

$$= (3.121) \frac{2.83}{2} \ \pi^{1/4} \ (A_C A_W)^{3/4}$$

$$= (3.121) \frac{2.83 \times 1.331}{2} \ (A_C A_W)^{3/4}$$

$$V_{wg} = 5.9\,(A_C A_W)^{3/4}$$

$$(A_C A_W)^{3/4} = \left(\frac{P \times 10^8}{4\, f\, B\, S\, K\, J}\right)^{3/4} = \frac{10^6}{2.835}\left(\frac{P}{f\, B\, S\, K\, J}\right)^{3/4}$$

$$V_{wg} = 2.08 \times 10^6 \left(\frac{P}{f\, B\, S\, K\, J}\right)^{3/4} \qquad (7)$$

$$P_W = \rho\, J^2\, K\, V_{wg}$$

For copper, the resistivity at a temperature of 20°C is 99×10^{-6} ohm-inches. The temperature coefficient of resistance is 0.00393. Resistivity may be written as a function of temperature, T, as follows:

$$\rho = 99 \times 10^{-6}\left[1 + .00393\,(T-20)\right]$$

$$\rho = (.39\,T + 91.2)\,10^{-6}$$

Let $T = T_1 + \Delta T$

where: T_1 = Initial starting temperature

ΔT = Temperature rise in the winding

$$\rho = (.39\,T_1 + .39\,\Delta T + 91.2)\,10^{-6}$$

$$\Delta T = \frac{1}{C_S} \times \frac{P_W\, t}{3600\, V_{wg} K}$$

where:

C_S = specific heat of copper in $\frac{\text{watt-hours}}{\text{in.}^3\,°C}$

The specific heat for copper is given as 0. 092 $\frac{\text{calories}}{\text{gm °C}}$

To convert to desired dimension:

$$C_S = 0.092 \frac{\text{calories}}{\text{gm °C}} \times 8.89 \frac{\text{gm}}{\text{cm}^3} \times \frac{1}{.061} \frac{\text{cm}^3}{\text{in.}^3} \times 1.163 \times 10^{-3} \frac{\text{watt-hours}}{\text{calories}}$$

$$C_S = 15.55 \times 10^{-3} \frac{\text{watt-hours}}{\text{in.}^3\ \text{OC}}$$

$$\Delta T = \frac{P_W\, t}{15.55 \times 10^{-3} \times 3600\, V_{wg} K} = \frac{P_W t}{56\, V_{wg} K} = .0179 \frac{P_W t}{V_{wg} K} \qquad (8)$$

$$.39\, \Delta T = .00696 \frac{P_W t}{V_{wg} K}$$

$$:\rho = (.39\, T_1 + .00696 \frac{P_W t}{V_{wg} K} + 91.2)\, 10^{-6}$$

$$P_W = (.39\, T_1 + .00696 \frac{P_W\, t}{V_{wg} K} + 91.2)\, 10^{-6}\, J^2\, K\, V_{wg}$$

$$P_W = .39 \times 10^{-6}\, T_1\, J^2\, K\, V_{wg} + .00696 \times 10^{-6} \frac{P_W t\, J^2 K\, V_{wg}}{K\, V_{wg}} + \frac{91.2 \times 10^{-6}}{J^2\, K\, V_{wg}}$$

$$P_W\, (1 - .00696 \times 10^{-6}\, t\, J^2) = .39 \times 10^{-6}\, T_1\, J^2\, K\, V_{wg} + 91.2 \times 10^{-6} J^2 K\, V_{wg}$$

$$P_W = \frac{(.39 \times 10^{-6}\, T_1 + 91.2 \times 10^{-6})}{1 - .00696 \times 10^{-6}\, t\, J^2}\, J^2\, K V_{wg} \qquad (9)$$

Substituting the values of P_W and V_{wg} back into the equation:

$$\Delta V_2 = \frac{Bt\, P_W}{3600} + V_{wg}$$

yields:

$$\Delta V_2 = \frac{Bt}{3600} \left(\frac{.39 \times 10^{-6}\, T_1 + 91.2 \times 10^{-6}}{1 - .00696 \times 10^{-6}\, t\, J^2} \right) J^2\, K \left(\frac{2.66 \times 10^8 P}{f\, \theta\, SKJ} \right)^{3/4} + \left(\frac{2.66 \times 10^8 P}{f\, \theta\, SKJ} \right)^{3/4}$$

$$\left(\frac{f\,B\,S}{P}\right)^{3/4} \Delta V_2 = \left(\frac{1.08 \times 10^{-10}\, T_1 + 2.53 \times 10^{-8}}{1 - .00696 \times 10^{-6}\, t\, J^2}\right) Bt\, J^2 K \left(\frac{2.66 \times 10^{8}}{J\,K}\right)^{3/4} + \left(\frac{2.66 \times 10^{6}}{J\,K}\right)^{3/4} \qquad (10)$$

Derivation of Equation for Winding Temperature Rise

From equation (8):

$$\Delta T = .0179 \frac{P_W\, t}{V_{wg} K}$$

Substituting for P_W from equation (9):

$$\Delta T = .0179 \frac{t}{V_{wg} K} \times \frac{.39 \times 10^{-6} T_1 + 91.2 \times 10^{-6}}{1 - .00696 \times 10^{-6}\, J^2\, t}\, J^2\, K\, V_{wg}$$

$$\Delta T = \frac{(.00696 \times 10^{-6}\, T_1 + 1.63 \times 10^{-6})\, J^2\, t}{1 - .00696 \times 10^{-6}\, J^2\, t}$$

Multiplying numerator and denomination by 10^9:

$$\Delta T = \frac{(6.96\, T_1 + 1630)\, J^2\, t}{10^9 - 6.96\, J^2\, t} \qquad (11)$$

APPENDIX C

TRANSISTOR VOLUME CALCULATIONS

APPENDIX C

TRANSISTOR VOLUME CALCULATIONS

1. DERIVATION OF SYSTEM VOLUME DUE TO TRANSISTOR LOSSES

Considering only the battery and converter transistors in the system, the volume of these components is:

$$V_T = V_B + V_Q$$

where V_T = Total volume, in in.^{3}

V_B = Battery volume, in in.^{3}

V_Q = Transistor volume, in in.^{3}

V_B has been shown to be

$$V_B = AV + BR$$

where: V = Battery terminal voltage, in volts

R = Battery rating, in watt-hours

A = Constant, with dimensions of $\frac{\text{in.}^3}{\text{volts}}$

B = Constant (dependent on battery regulation) with dimensions of $\frac{\text{in.}^3}{\text{watt-hours}}$

The required battery rating (R) is dependent on the load requirements and the power loss of the transistors.

$$R = (E_L \times I_L \times t + P_{T(AVG)} \times t)\ \frac{1}{3600}$$

where:

E_L = Load voltage, in volts.

I_L = Load current, in amperes.

t = Actual load time, in seconds.

$P_{T(AVG)}$ = Total average transistor power losses, in watts.

The total average transistor power losses are comprised of both switching and conduction losses. The switching losses are functions of oscillator frequency.

$$P_{T(AVG)} = P_{SW} + P_{CON}$$

where: $P_{SW} = P_{RT} + P_{ST} + P_{FT}$

P_{RT} = Rise time loss, in watts

P_{ST} = Storage time loss, in watts

P_{FT} = Fall time loss, in watts

The conduction losses arise from leakage current and base drive currents, and are not functions of oscillator frequency. Losses occur during both the ON and OFF switched modes, and averaged by dividing by 2.

$$P_{CON} = \frac{(P_{ON} + P_{OFF})}{2}$$

where:

$$P_{ON} = V_{CE(SAT)} I_S + V_{BE} \frac{I_S}{h_{FE}}$$

$$P_{OFF} = (2 V_S I_{CO} + V_{EBO} I_{EBO})$$

and:

V_S = Battery source voltage, in volts

I_S = Battery source current, in amperes

Thus, the system volume is a function of converter oscillator frequency, due to the battery volume needed to supply power to compensate for transistor switching losses.

$$V_T = AV + \frac{B}{3600} (E_L I_L t + P_{T(AVG)} t) + V_Q$$

$$= AV + \underbrace{\frac{Bt}{3600} (E_L I_L)}_{\Delta V_1} + \underbrace{\frac{Bt}{3600} (P_{T(AVG)})}_{\Delta V_2} + V_Q$$

where:

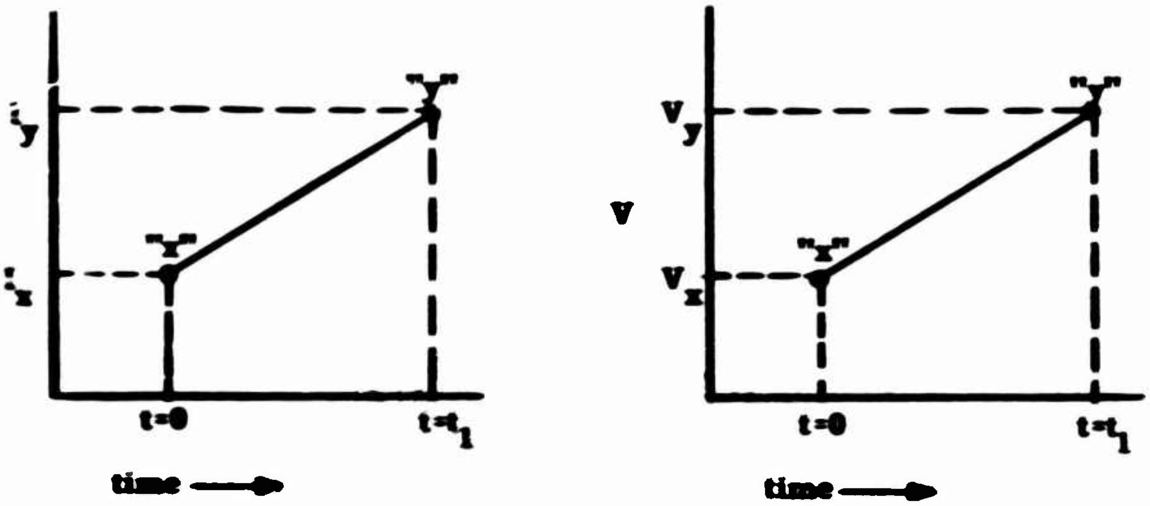
ΔV_1 = Component of system volume due to load power delivered.

ΔV_2 = Component of system volume due to transistor losses.

2. DERIVATION OF TRANSISTOR SWITCHING LOSSES

The general case of a transducer switching from point "x" to point "y" is shown in Figure C-1.

Figure C-1 - LINEAR SWITCHING



Assuming switching which is linear with time,

$$i = I_x + \left(\frac{I_y - I_x}{t_1}\right) t \qquad (1)$$

and

$$v = V_x + \left(\frac{V_y - V_x}{t_1}\right) t \qquad (2)$$

The power dissipated during the switching interval t_1 is defined as:

$$P = \frac{1}{T} \int_0^{t_1} v\, i\, dt \qquad (3)$$

where T is the period over which the power is averaged.

Substituting equations (1) and (2) in equation (3),

$$P = \frac{1}{T}\int_{o}^{t_1} \left\{ V_x I_x + \left[V_x \left(\frac{I_y - I_x}{t_1} \right) + I_x \left(\frac{V_y - V_x}{t_1} \right) \right] t + \left[\left(\frac{V_y - V_x}{t_1} \right) \left(\frac{I_y - I_x}{t_1} \right) t^2 \right] \right\} dt$$

$$P = \frac{1}{T} \left[V_x I_x t_1 - V_x \left(\frac{I_y - I_x}{2\,t_1} \right) t_1^2 + I_x \left(\frac{V_y - V_x}{2\,t_1} \right) t_1^2 + \frac{(V_y - V_x)(I_y - I_x)}{3\,t_1^2} t_1^3 \right]$$

Substituting $f = \frac{1}{T}$ for a transistor oscillator and simplifying yields:

$$P = f t_1 \left[\frac{1}{6} (V_x I_y + V_y I_x) + \frac{1}{3} (V_x I_x + V_y I_y) \right] \tag{4}$$

APPENDIX D

LETTERS OF INQUIRY

H O N E Y W E L L

I N C.

April 4, 1966

Magnetic Metals Company
Heyes Avenue at 21st Street
Camden 1, New Jersey

Attention: Mr. R. T. Harrison

Dear Sir:

Honeywell is presently funded to develop a dc/dc converter with extremely high power densities. We are attempting to handle 10 kilowatts of power with a 5 pound weight limit. Our initial design calculations indicate that the converter transformer must be operated at a frequency in excess of 25 KHz to approach the size and weight requirements. From a semiconductor standpoint the most efficient AC wave shape to use is a square wave voltage. Because the transformer size and weight is the pacing item for this converter, it is necessary to select the very best material and configuration for use in this system. It is anticipated that the power losses of this transformer may be as high as one kilowatt.

In order to achieve the highest power density in a transformer within the limitation of the losses which are permissible, it would appear that the maximum flux density and the core loss per cycle at the exciting wave shape and frequency are the two most important considerations. We would like to get core material parameters and characteristics to determine an optimum design. These characteristics will include:

1. Maximum flux density
2. Core loss for various square wave frequencies and flux densities.
3. The specific gravity
4. The specific heat
5. The variation of parameters (1) and (2) through a temperature range from -65 to +250 F.

We realize that core loss characteristics are usually measured for sine wave excitation. If data for square wave excitation is not available, could you indicate any predicted performance or scaling factors to use with sine wave characteristics?

Please contact Mr. Richard L. Carlson, Project Engineer, (935-5155, Ext. 8265) if additional information concerning these requirements would be helpful.

Sincerely yours,

R. L. Carlson,
Project Engineer

RLC:vs

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HONEYWELL

INC.

April 8, 1966

Motorola Semiconductor Products, Inc.
7515 Wayzata Boulevard
Suite 204
Minneapolis, Minnesota 55426

Attn: Glen Johnson

Subject: Transistors for 10 KW Converter

Dear Mr. Johnson:

We currently have a funded study contract to make design recommendations for a battery operated, high power density, DC/DC converter for use in a missile system. The principle design constraints in this study are the weight and volume of the unit. Consequently, the efficiency and associated temperature rise within the unit become major design considerations.

The required power output of the converter is 8.2 KW at several DC levels and the estimated power input is 10 KW (82% efficiency). The transistor losses were estimated at 800 watts.

The transistors will be operated in the switching mode of operation with significant overdrive to hold the transistor well into saturation during the "on" period and the base drive will be shaped to enhance switching. In order to meet the weight and volume requirements, the switching frequency must be greater than 25 KHz. The transistor mounting base temperature will not exceed 100°C.

In this application, the desirable transistor characteristics are:

- Low $V_{CE(SAT)}$
- High Gain
- Fast Switching
- High Current Rating
- Ratio of $\frac{V_{CE(MAX)}\ I_{C(MAX)}}{\text{Losses}}$ 12.5

losses = saturation loss + switching loss @ 25 KHz + base drive loss + cutoff loss.

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A recommended battery voltage will be determined as a result of this study and will be based primarily on the $V_{CE(MAX)}$ rating of the transistor and the type of converter circuitry used. However, the battery manufacturer prefers that the battery voltage be in the range of 25 to 100 volts.

If you have a transistor which you would recommend, please provide the specifications describing the device. If available, we would also appreciate information concerning the optimum base drive voltage and/or current wave forms to minimize the transistor losses.

If the transistor is under development, indicate probable parameters and the estimated availability date.

We will need anticipated performance data by May 15, 1966 and feasibility units by January 1967 in order to consider any new device.

Please address your written replies to my attention by May 6, 1966 for use in this study. If additional technical information is required, please contact Mr. Richard Carlson, Project Engineer, at (612) 935-5155, ext. 8265.

Sincerely,

HONEYWELL INCORPORATED

J.W. Brumbaugh, Engineer
Applications & Specifications
Mail Station 832

JWB/jh

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3. REPORT TITLE

Silver-Zinc Power Supply

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

FOURTH QUARTERLY PROGRESS REPORT 5/1/66 - 7/31/66

5. AUTHOR(S) (Last name, first name, initial)

CHIREAU, ROLAND F.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
15 JULY 1966	149	

8a. CONTRACT OR GRANT NO. AF 33(615)2663	9a. ORIGINATOR'S REPORT NUMBER(S) No. 4
b. PROJECT NO. 8173	
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13. ABSTRACT

1. "All battery" design approaches using duplex electrodes (pile construction) are described and design parameters compiled.
2. The experimental work performed to verify the various cell and battery designs has been outlined. Data and test results are analyzed.
3. Design guidelines for a 1500 VDH, 750 watt-hour battery module are summarized.
4. Extensive data on battery size and weight versus battery voltage have been compiled for batteries having outputs of 2 KW to 20 KW. Formulae expressing the weight and volume of batteries as a function of nominal battery terminal voltage, watt-hour rating and percent regulation are presented for batteries utilizing conventional (individual) cells.
5. The study phase of the DC-DC converter development program is in progress. A report which documents the effort expended by The Ordnance Division of Honeywell, Inc. during the preceding quarter is included in the Appendix of this report.

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